WIRELESS EXPERIMENTATION WITH SDR: THE WAY TO DRIVE INNOVATION

INGRID MOERMAN

WIRELESS INNOVATION

- HOW?
- SDR IS KEY
- FUTURE VISION

WIRELESS INNOVATION – HOW?

WIRELESS INNOVATION - HOW?

THEORETICAL ANALYSIS

☺ Link level models & analysis
- PHY design
- Channel models

☺ (Best case) system capacity models

☺ Static & deterministic systems

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☹ Dynamic & non-deterministic systems

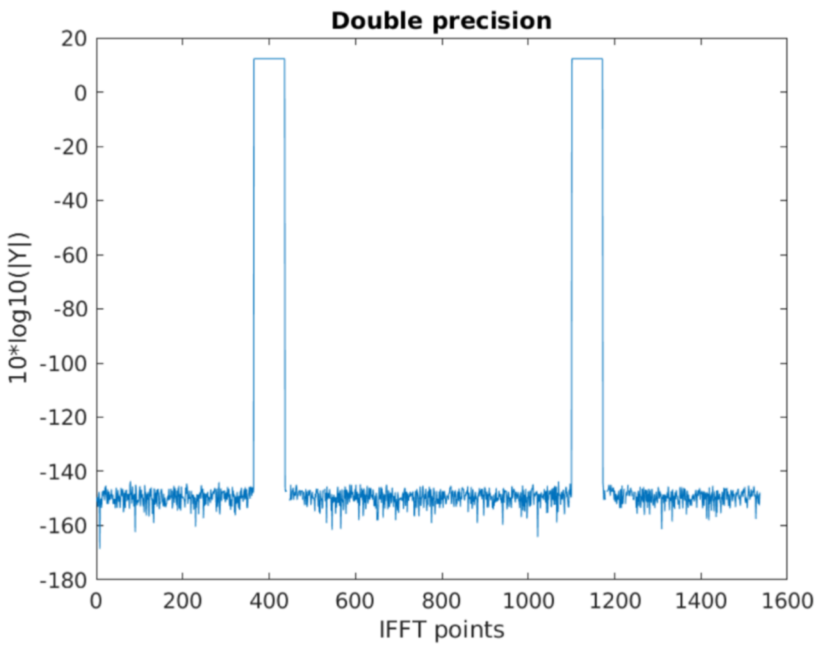
☹ Hard to model beyond PHY/link

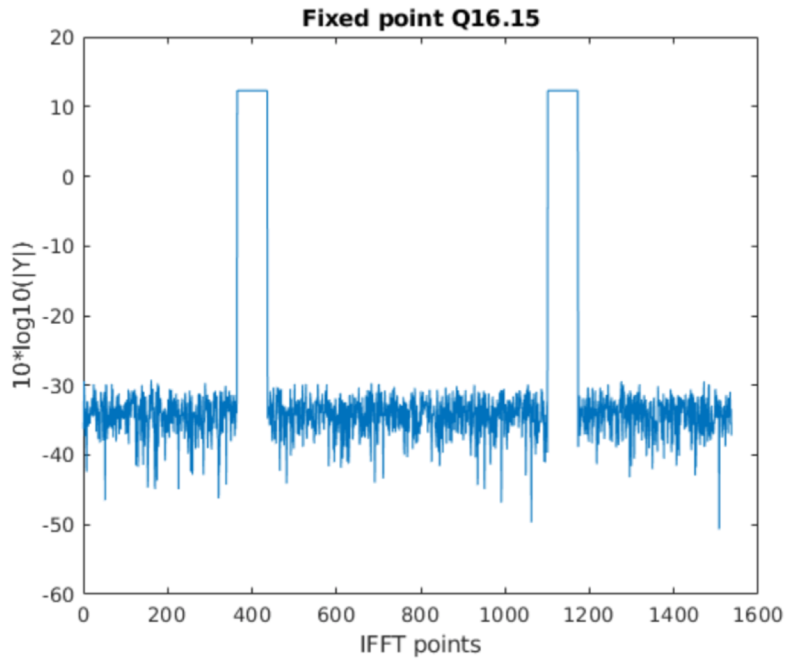
☹ Hard to model realistic environments and wireless impairments: interference, multi-path, fading, shadowing…

☹ Hard to take into account hardware/implementation related constraints

HARDWARE/IMPLEMENTATION RELATED CONSTRAINTS

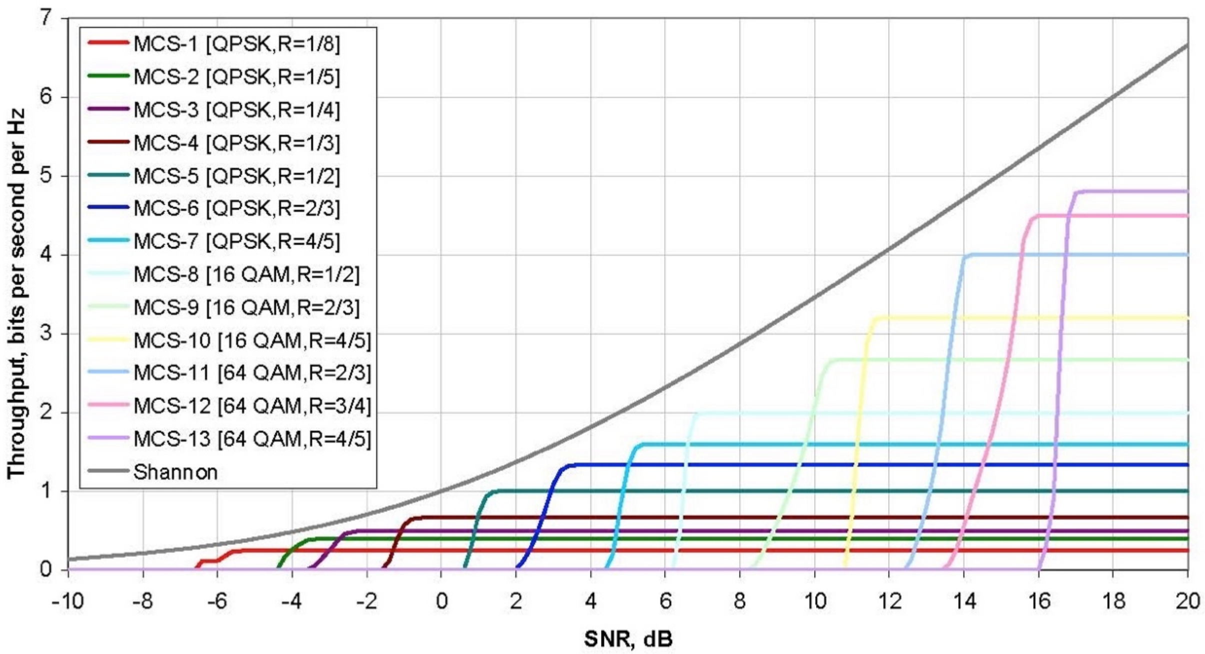
- Example: Signal-to-Noise Ratio (SNR)
  - Double precision is not supported on ASIC/FPGA ➜ noise floor elevation due to quantization





THEORETICAL ANALYSIS HARDWARE/IMPLEMENTATION RELATED CONSTRAINTS

- Example: Signal-to-Noise Ratio (SNR) for LTE
  - Double precision is not supported on ASIC/FPGA ➜ noise floor elevation due to quantization



Theoretical analysis may lead to WRONG coverage and capacity estimations

WIRELESS INNOVATION - HOW?

THEORETICAL ANALYSIS	SIMULATION
☺ Link level models & analysis • PHY design • Channel models	☺ Network level analysis
☺ (Best case) system capacity models	☺ Scalability analysis
☺ Static & deterministic systems	☺ Easy implementation
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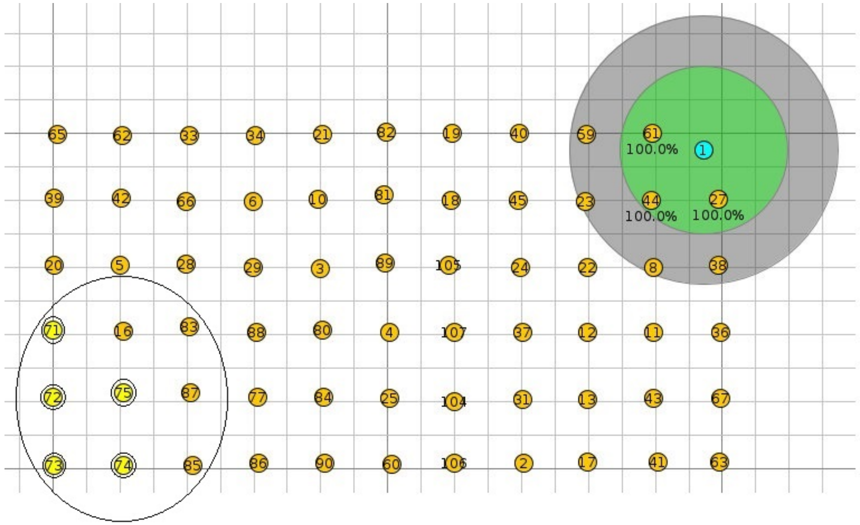
SIMULATION

LIMITED REALISM OF SIMULATORS

Unrealistic grid topologies

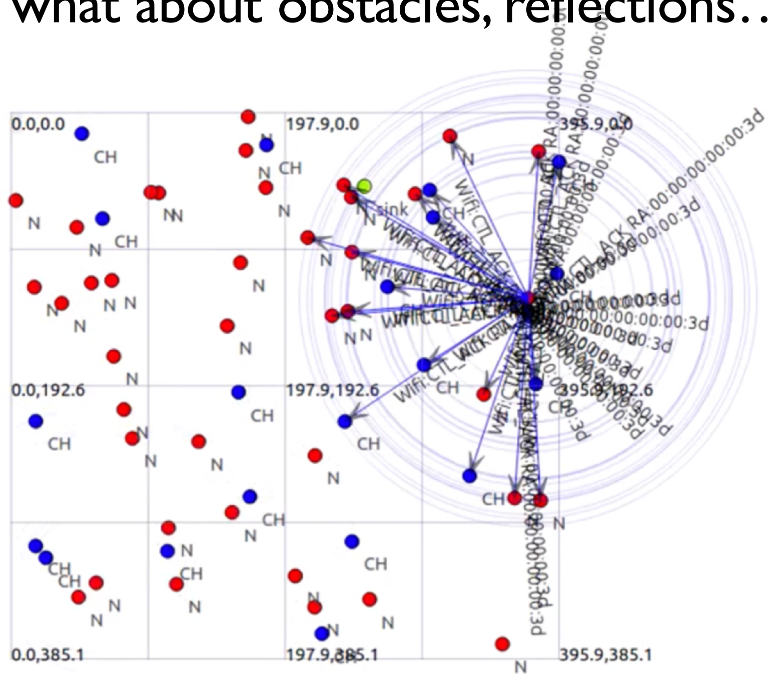
artificial multi-hop domain



M Ali Lodhi et al., KSII Transactions on Internet and Information Systems, Vol. 11, No. 4, Apr. 2017

Oversimplified channel models

what about obstacles, reflections…?

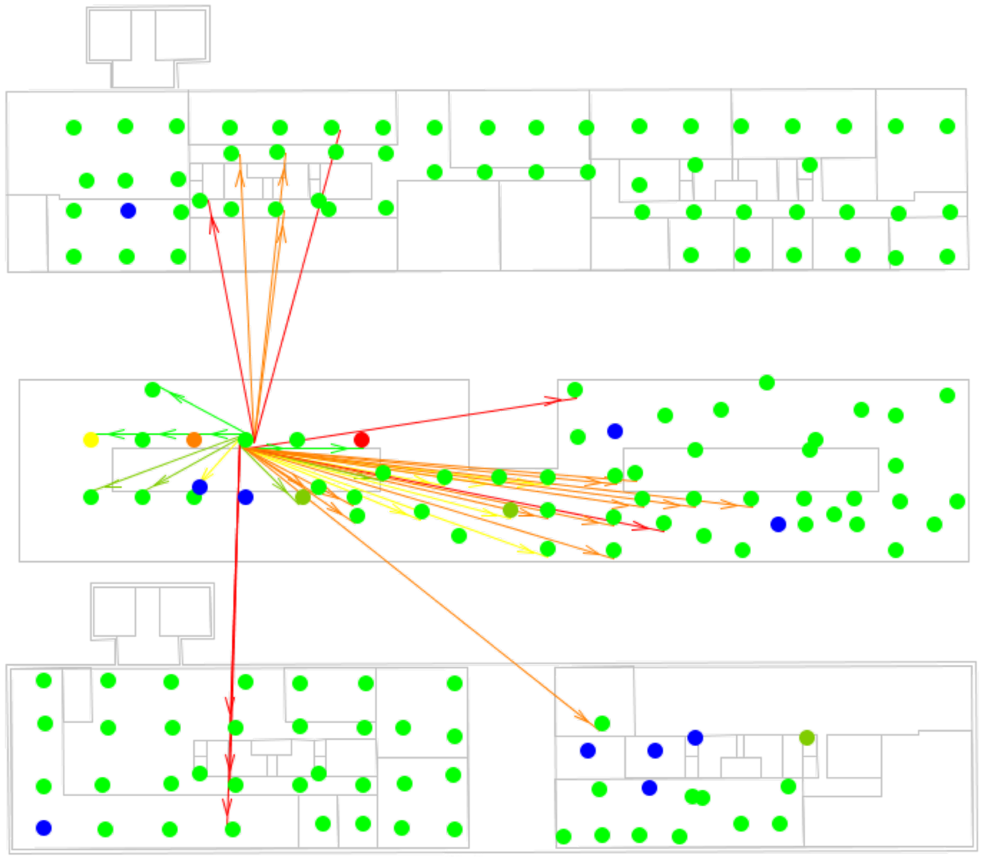


https://youtu.be/8Vm2J1g8faU

SIMULATION

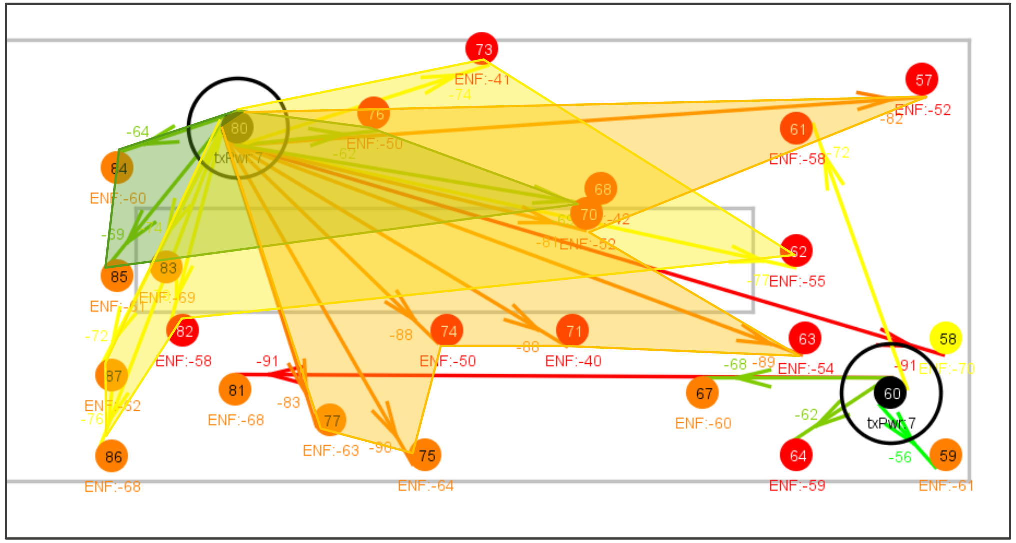
LIMITED REALISM OF SIMULATORS

- Example: real-life collision domain
  - Influenced by obstacles, wall & ceilings, antenna



3 floors

18 x 90 m^2



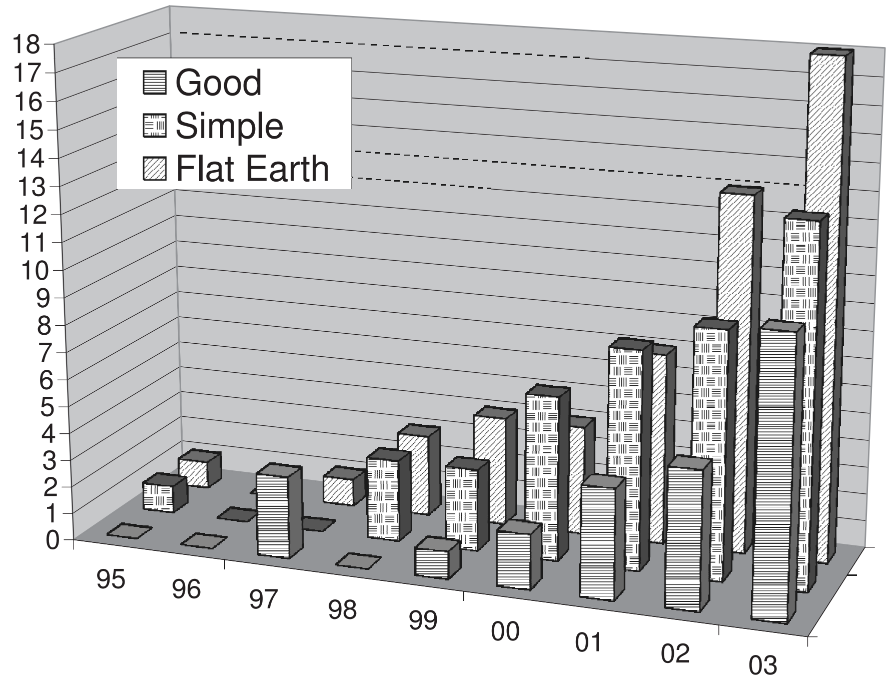
SIMULATION

WRONG ASSUMPTIONS

- The world is flat
- There are only line-of-sight transmissions
- The transmission area of a radio is circular (perfect omnidirectional antennas)
- All radios have equal range
- Radio links are perfectly symmetrical
- Signal strength is a simple function of distance
- Transmit power range is identical for all devices
- Events are uniformly distributed in sensor networks and every event is independent of other events
- …

STILL MANY ”SIMPLE” & “FLAT EARTH” SIMULATIONS TODAY!

Number of papers in each year of Mobicom and MobiHoc



Flat Earth: 2D, no packet loss
Simple: simple “more realistic” model, includes delay & packet losses
Good: empirical models based on extensive experimental data

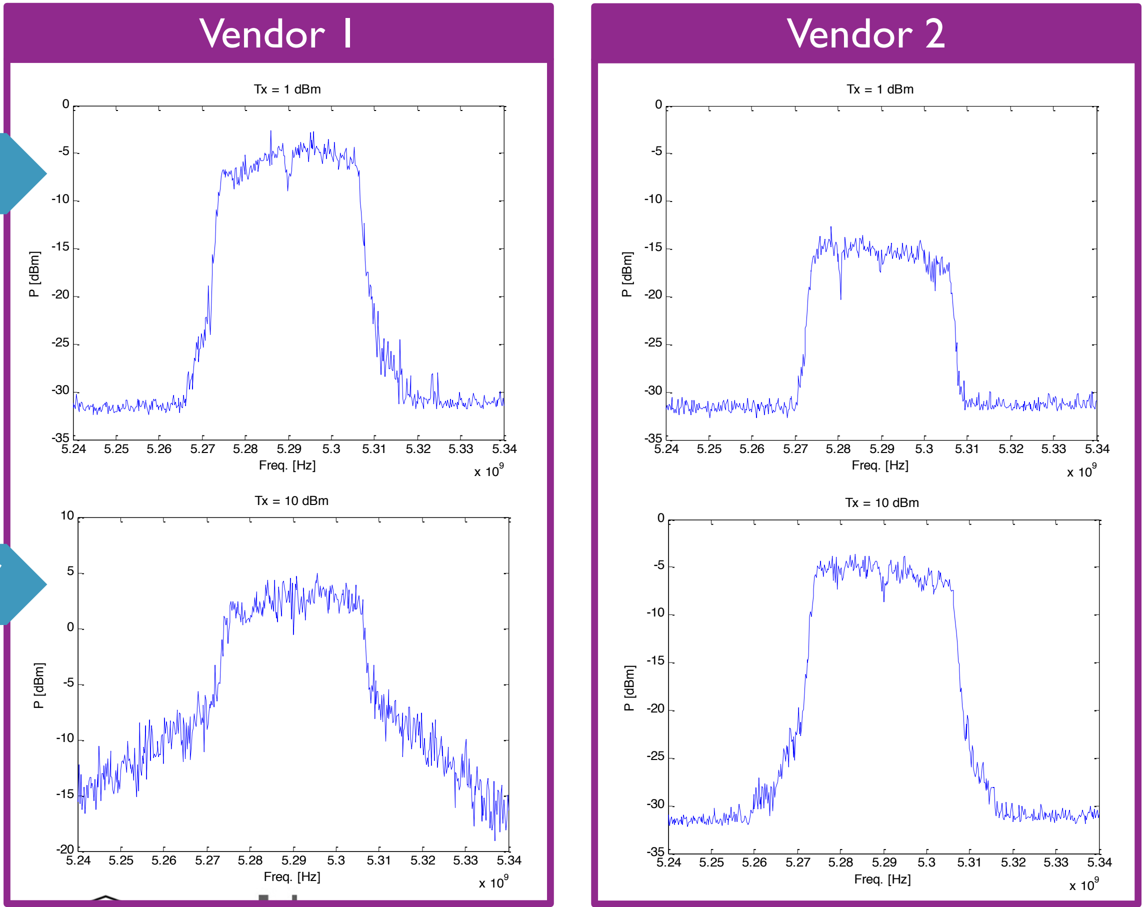
Newport, C., Kotz, D., Yuan, Y., Gray, R. S., Liu, J., & Elliott, C. (2007). Experimental Evaluation of Wireless Simulation Assumptions, SIMULATION, 2007, 83(9), 643–661.

SIMULATION HARDWARE/IMPLEMENTATION RELATED CONSTRAINTS

- Example: hardware limitations of off-the-shelf Wi-Fi cards

Low Tx power (1dBm)

High Tx power (10 dBm)



Different Wi-Fi cards have different behavior in terms of Tx power and out-of-band emission

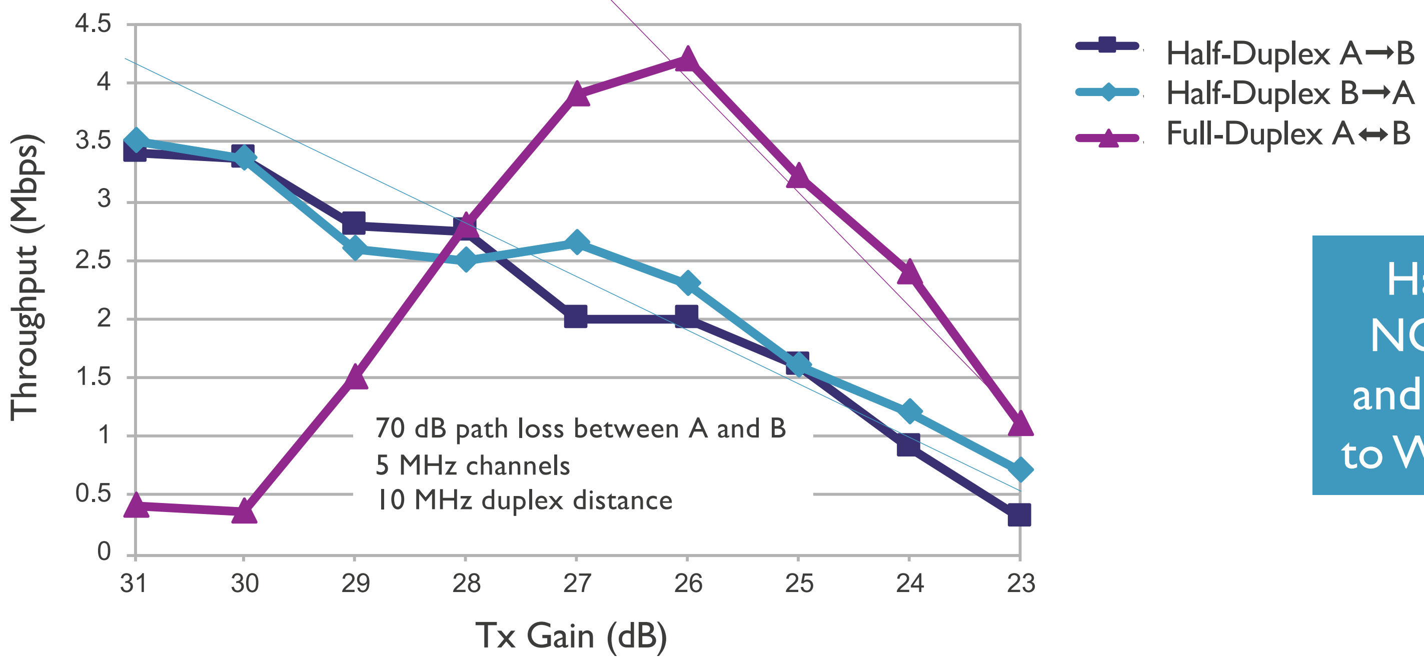
Simulations do not consider interference between “non-overlapping” channels

THEORETICAL ANALYSIS

SIMULATION

HARDWARE/IMPLEMENTATION RELATED CONSTRAINTS

- Example: full duplex operation and/or multi-radio operation
  - Non-linear gain + self-interference effects → distortion & noise floor elevation

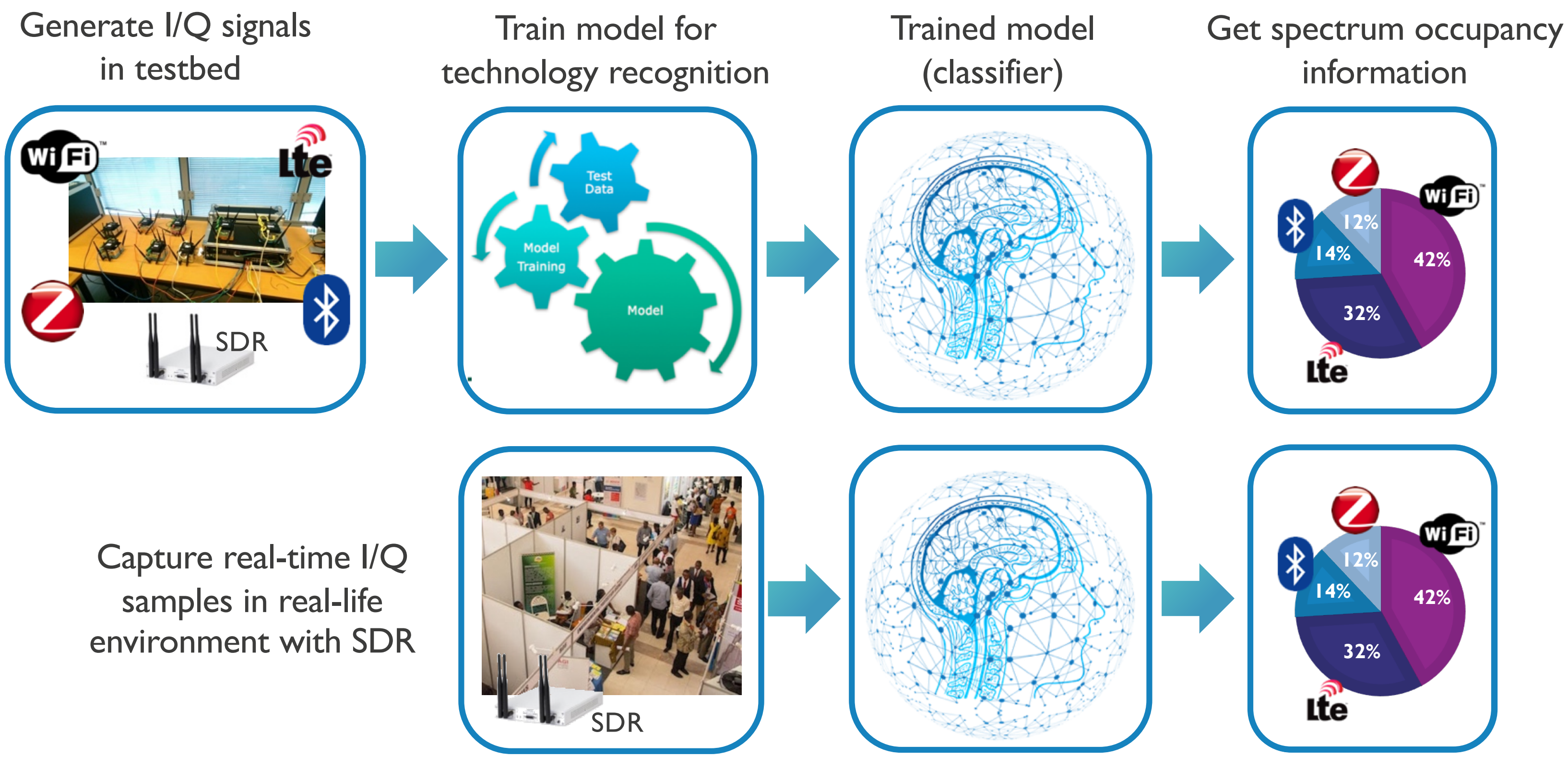


Hardware constraints are NOT considered in models and simulations and may lead to WRONG operation modes

SIMULATION

LIMITED REALISM OF SIMULATORS

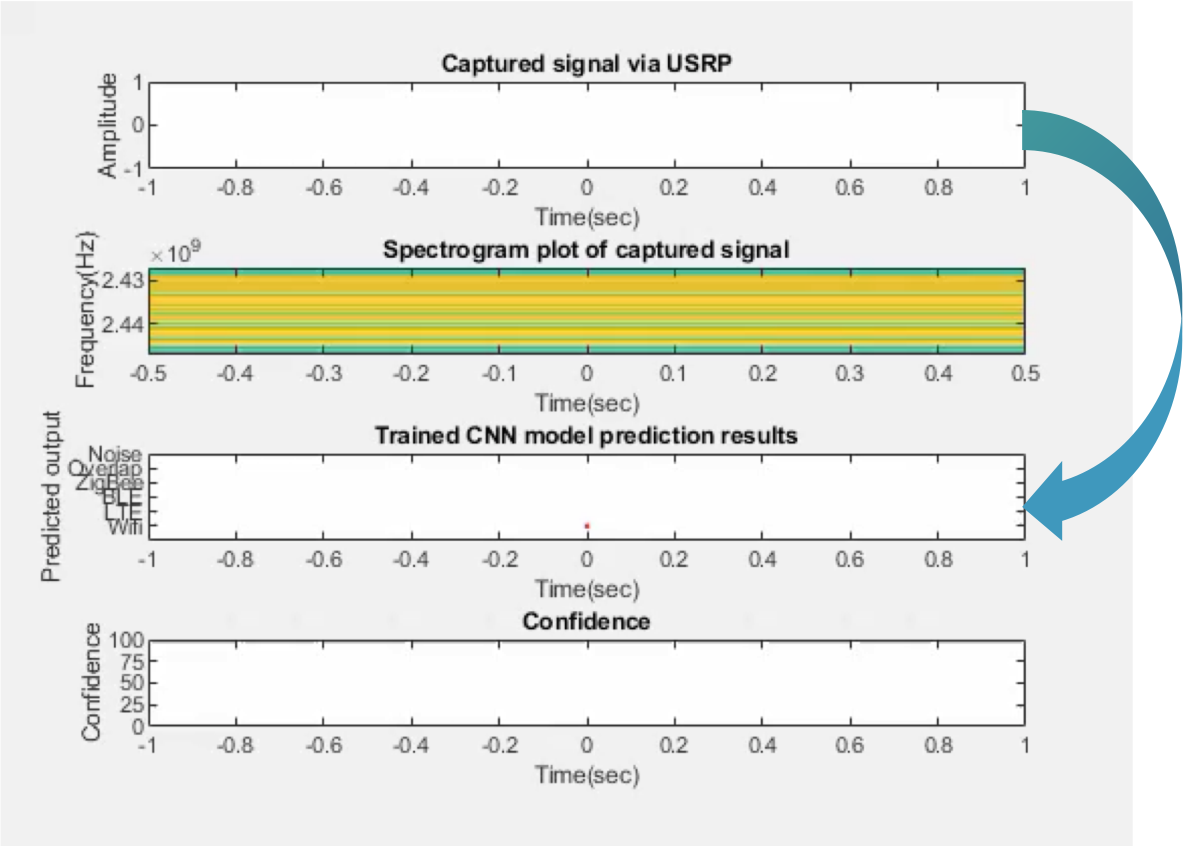
- Example: simulator for creating data sets for machine learning



Be careful with synthetic data!

SIMULATION LIMITED REALISM OF SIMULATORS

- Example: Real-life I/Q samples for creating data sets for machine learning



See demo @ INFOCOM2019

"Identification of LPWAN Technologies using Convolutional Neural Networks"

Wed. May 1st, 10:30 – 12:30

WIRELESS INNOVATION - HOW?

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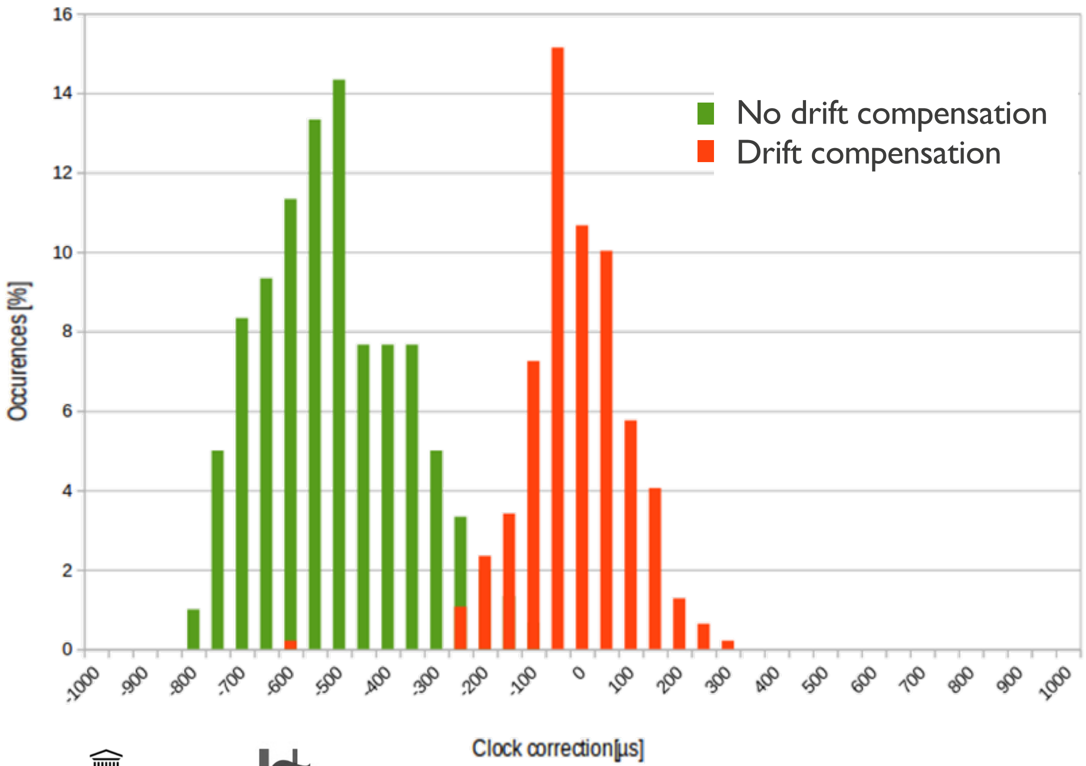
EXPERIMENTATION

- ☺ Realistic wireless environments (e.g. collision domain, coexistence, (self)interference, mobility…)
- ☺ Real hardware
- ☺ Real applications
- ☹ Limited by off-the-shelf hardware platforms and drivers
- ☹ More complex implementation
  - hardware dependent
  - often needs reverse engineering
- ☹ Small to medium scale experiments
- ☹ Reproducibility?

EXPERIMENTATION HARDWARE/IMPLEMENTATION RELATED CONSTRAINTS

- Example: time synchronization between nodes
  - A lot of clock drifts between different nodes → need for guard spaces



Time synchronization between wireless devices is still a big issue limiting MAC efficiency

Experiments with real hardware cannot be avoided

WIRELESS INNOVATION - HOW?

THEORETICAL ANALYSIS | **SIMULATION** | **EXPERIMENTATION**

FUNDAMENTAL RESEARCH ↔ SMART ENGINEERING

- Channel models
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Each method has it merits, pitfalls & limitations

Experimentation with real hardware cannot be avoided

The devil is in the detail!

INNOVATION = MULTIDISCIPLINARY RESEARCH + SMART ENGINEERING

WIRELESS EXPERIMENTATION – SDR IS KEY

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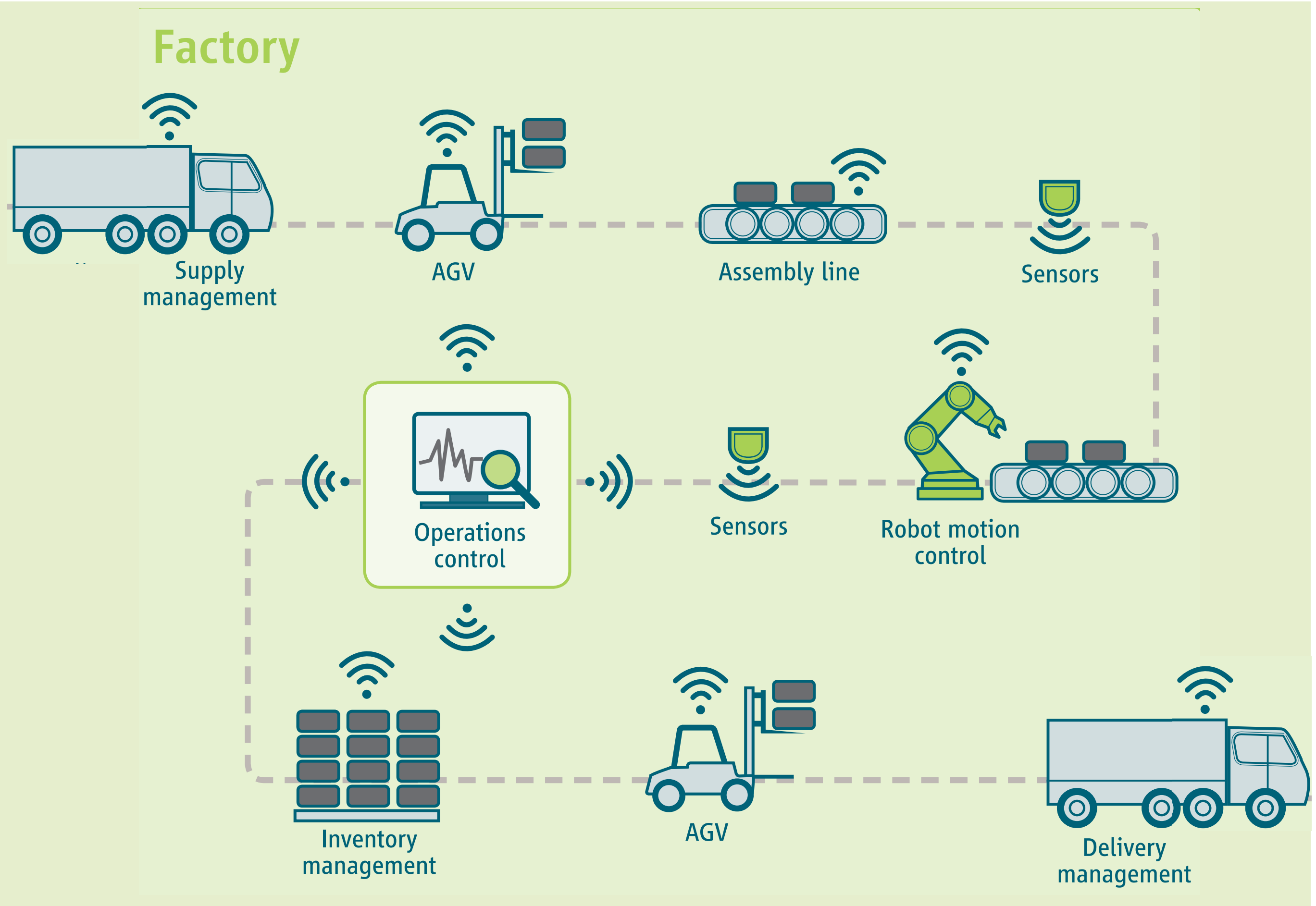
DRIVING SHOWCASE: INDUSTRY 4.0



5G ACIA
5G Alliance for Connected Industries and Automation

https://www.5g-acia.org/fileadmin/5G-ACIA/Publikationen/Whitepaper_5G_for_Connected_Industries_and_Automation/WP_5G_for_Connected_Industries_and_Automation_Korrektur_Download.pdf

DRIVING SHOWCASE: INDUSTRY 4.0

Use case (high level)		Availability	Cycle time	Typical payload size	# of devices	Typical service area
Motion control	Printing machine	>99.9999%	< 2 ms	20 bytes	>100	100 m x 100 m x 30 m
	Machine tool	>99.9999%	< 0.5 ms	50 bytes	~20	15 m x 15 m x 3 m
	Packaging machine	>99.9999%	< 1 ms	40 bytes	~50	10 m x 5 m x 3 m
Mobile robots	Cooperative motion control	>99.9999%	1 ms	40-250 bytes	100	< 1 km^2
	Video-operated remote control	>99.9999%	10 – 100 ms	15 – 150 kbytes	100	< 1 km^2
Mobile control panels with safety functions	Assembly robots or milling machines	>99.9999%	4-8 ms	40-250 bytes	4	10 m x 10 m
	Mobile cranes	>99.9999%	12 ms	40-250 bytes	2	40 m x 60 m
Process automation (process monitoring)		>99.99%	> 50 ms	Varies	10000 devices per km^2	

DRIVING SHOWCASE: INDUSTRY 4.0

5G ACIA
5G Alliance for Connected Industries and Automation

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HOW TO ACHIEVE DIVERSITY OF REQUIREMENTS

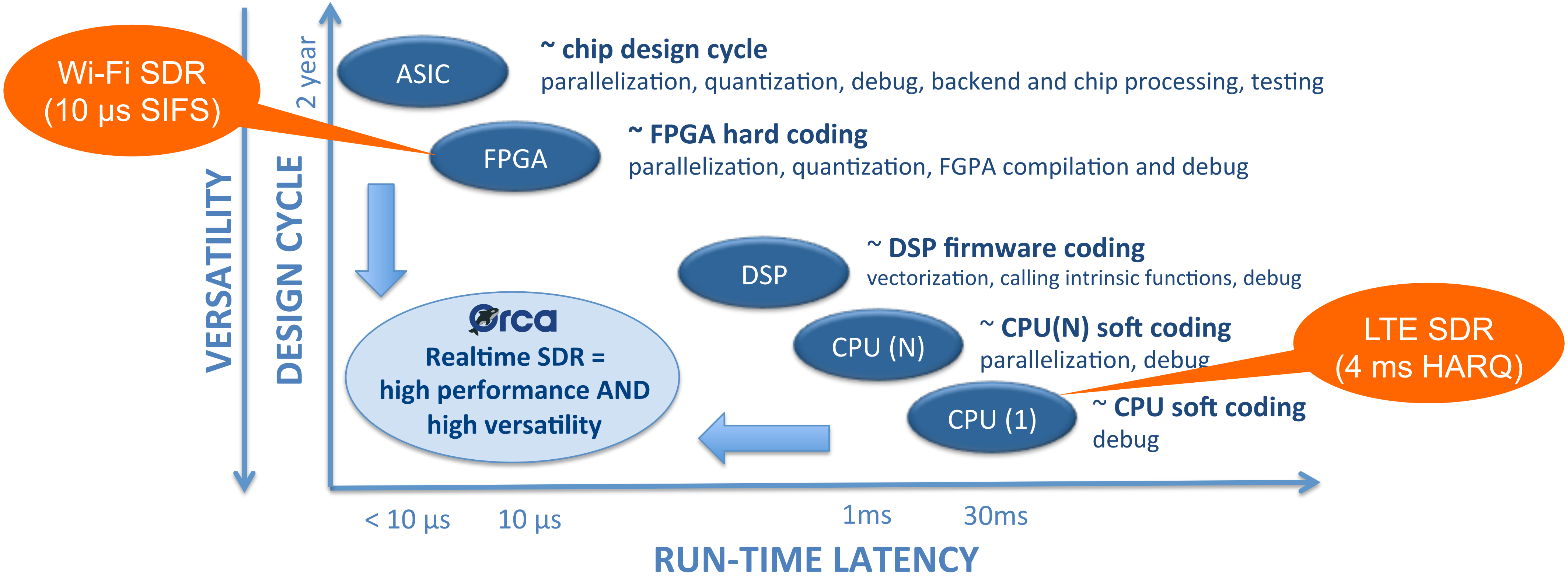
- WITH A SINGLE WIRELESS TECHNOLOGY?
- SHARING THE SAME SPECTRAL BANDS?

HOW DO WE CONTROL?

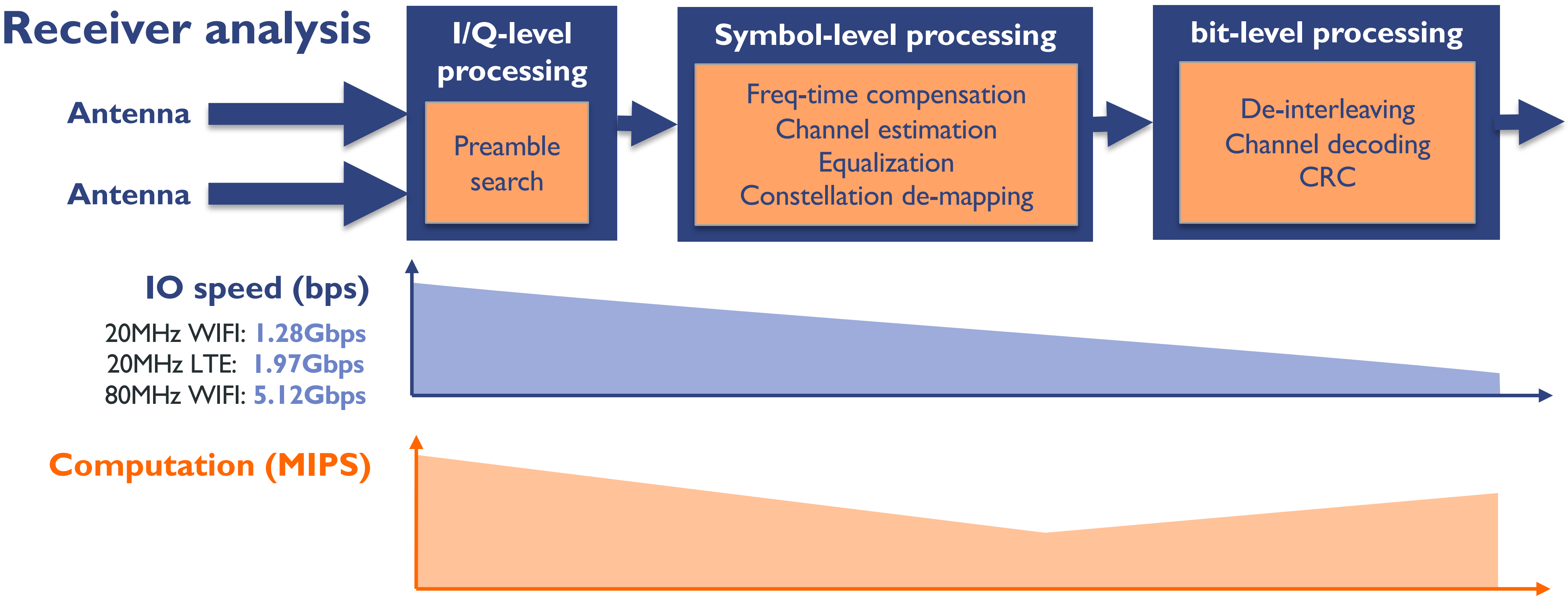
SCOPE

To offer mature, real-time and versatile SDR platforms in advanced wireless test facilities

Versatility = Flexibility + Reprogrammability

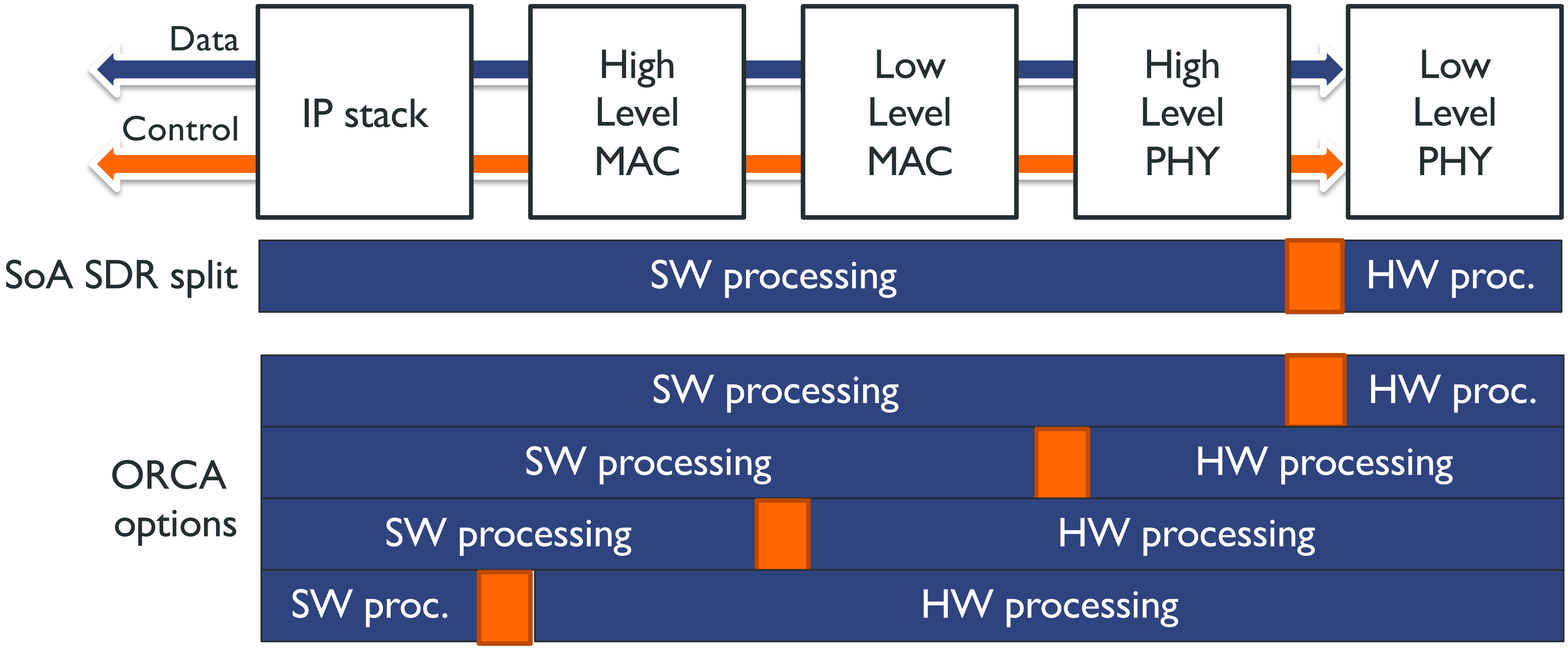


SW (VERSATILITY) / HW (PERFORMANCE) DILEMMA



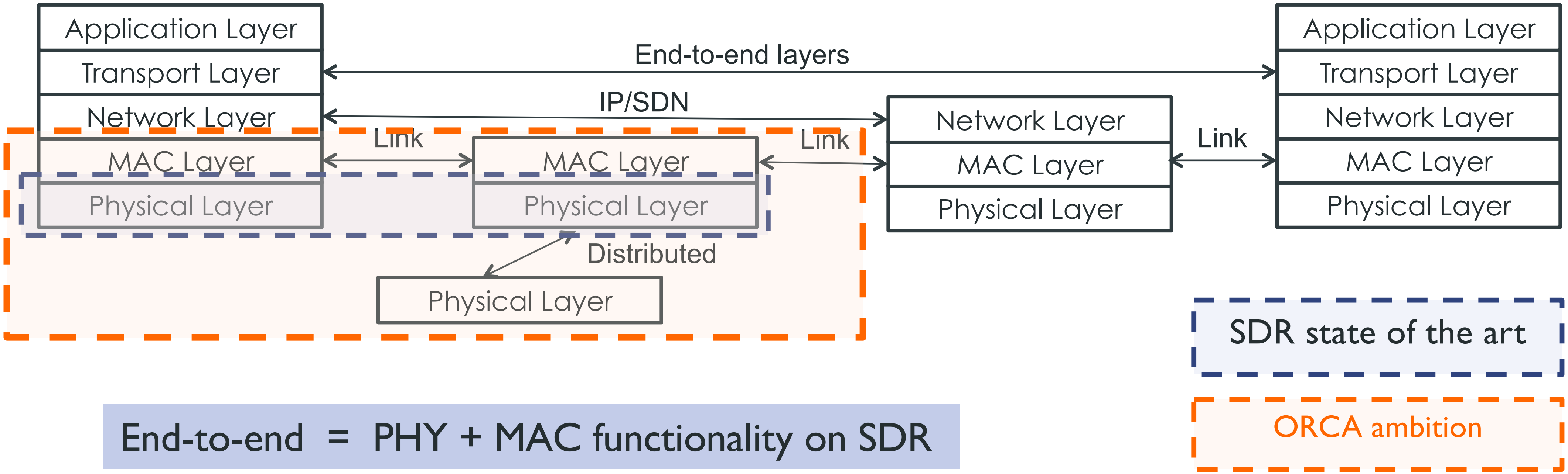
SW approach: → NOT REAL-TIME → NEED FOR HW ACCELERATION

ORCA AMBITION: TOWARDS MORE REAL-TIME IMPLEMENTATION



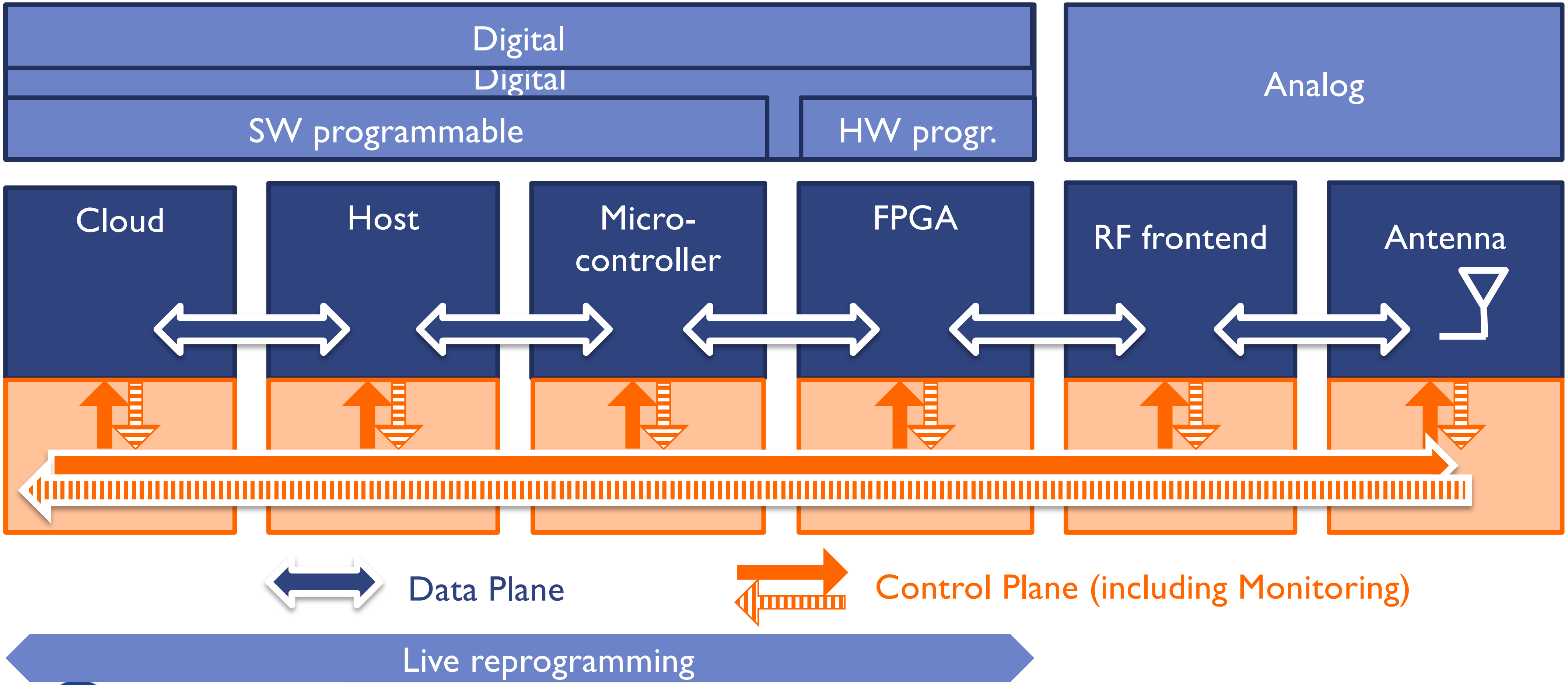
SCOPE

end-to-end networking experimentation

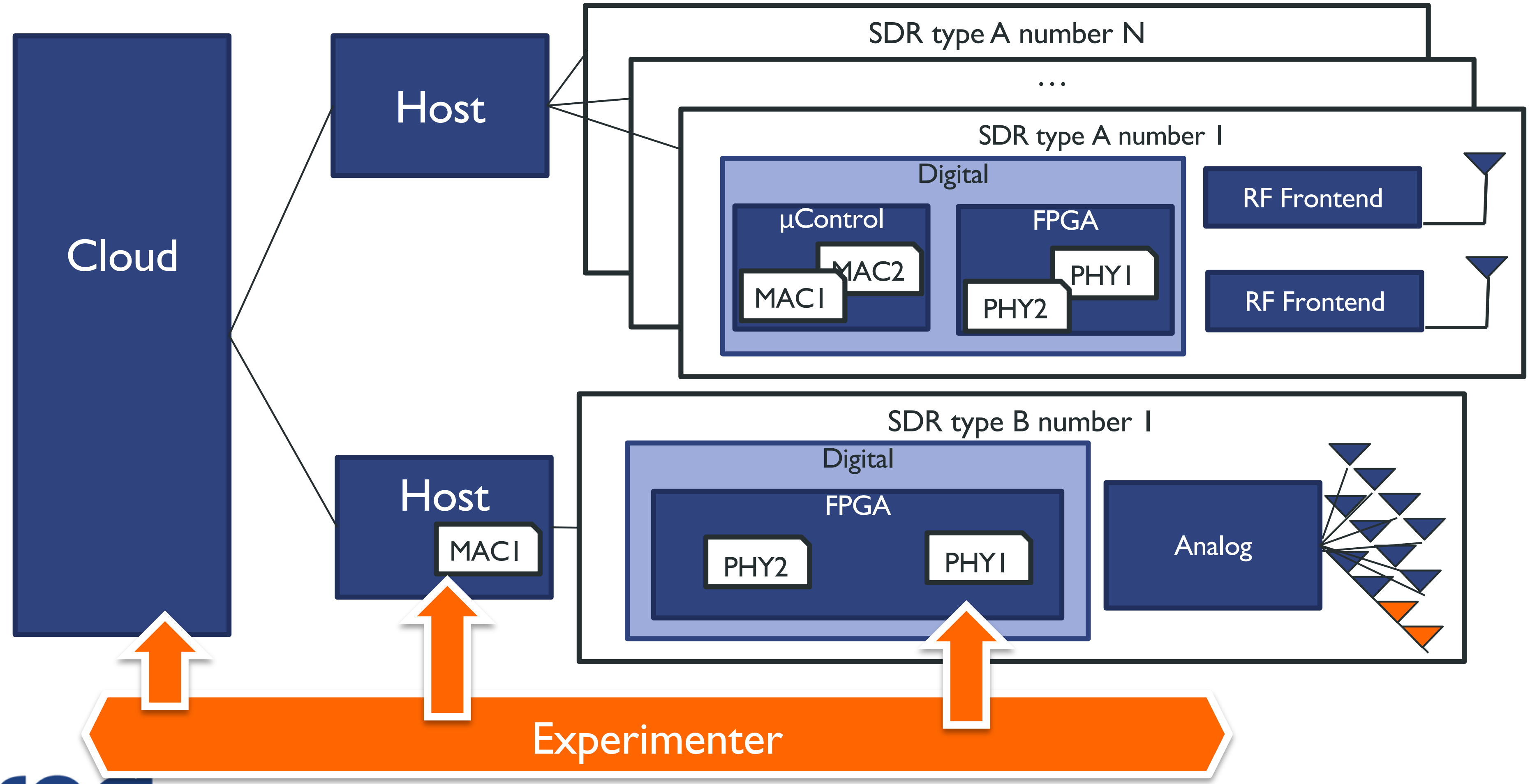


End-to-end = PHY + MAC functionality on SDR

SCOPE **Compose, reconfigure and reprogram** wireless devices at runtime

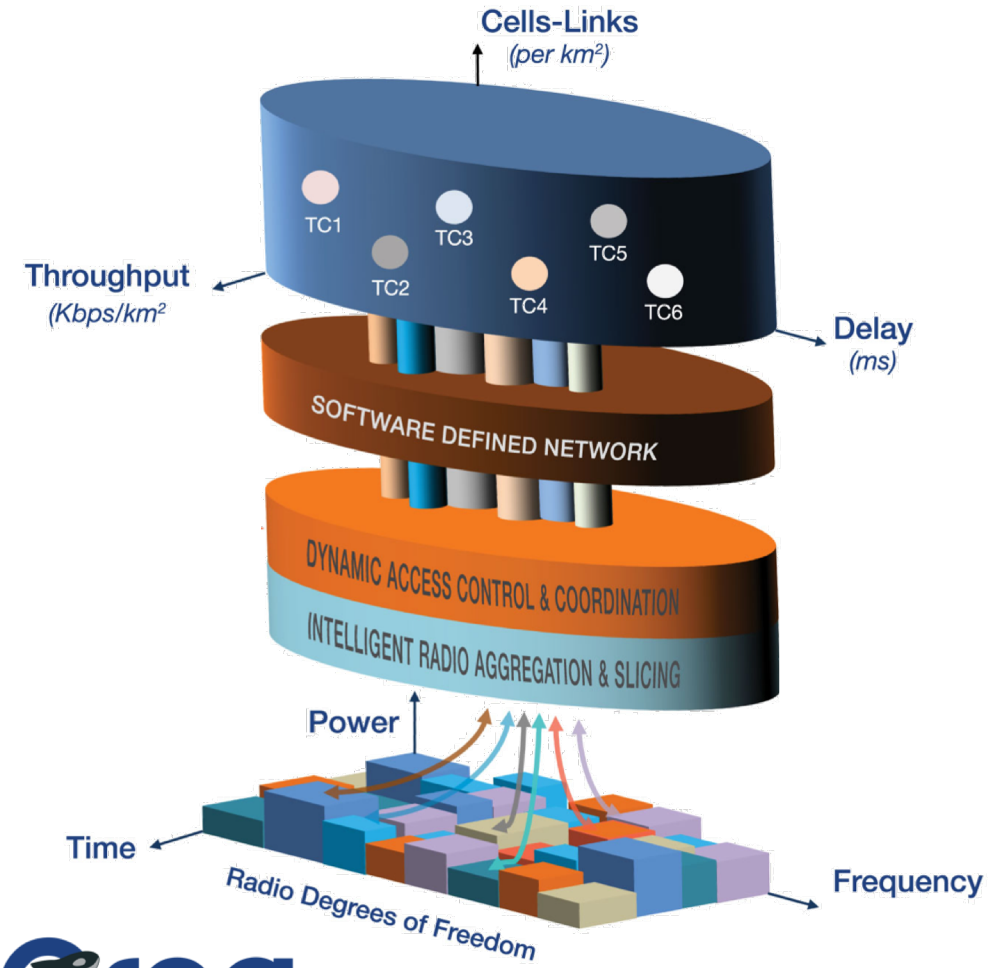


ORCA AMBITION: RUNTIME CONTROL OF MULTIPLE NETWORKED SDRs



SCOPE

Bridging **SDR** and **SDN**



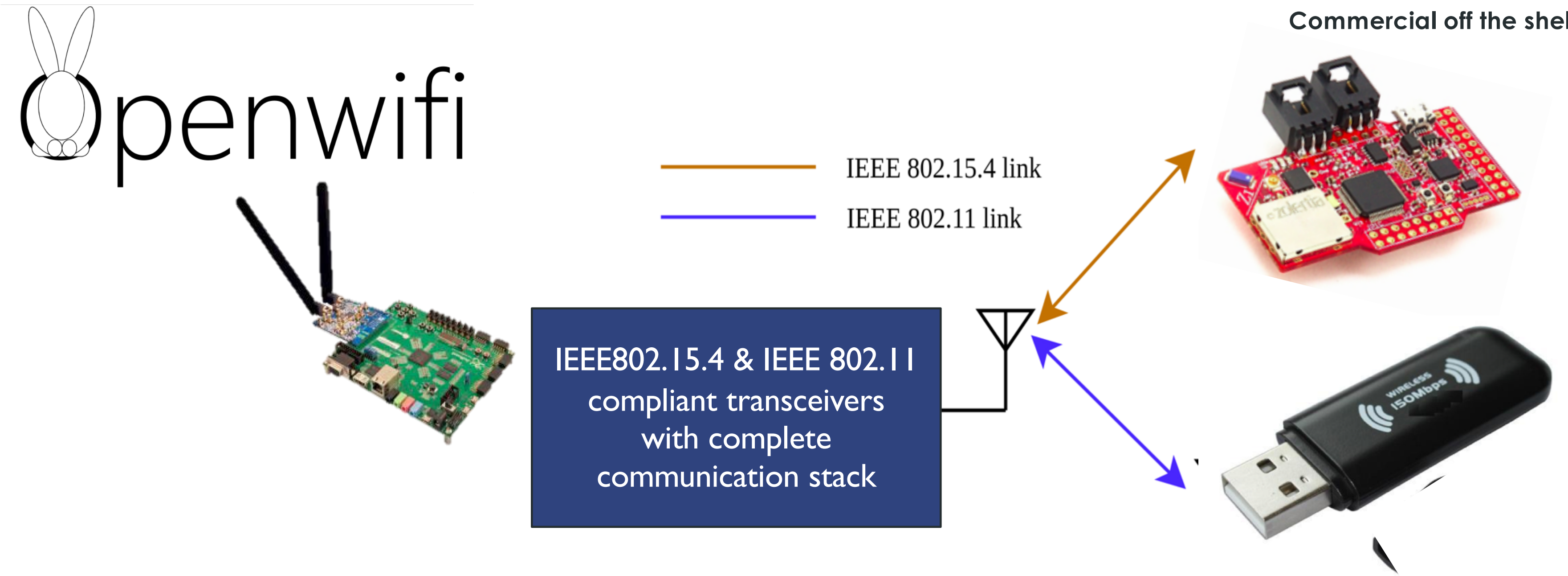
to drive end-to-end wireless network innovation by **bridging real-time SDR and SDN** exploiting maximum flexibility at radio level, medium access level and network level, to meet very diverse application requirements

MAPPING OF RADIO RESOURCE SLICES TO SDN FLOWS

SOME TECHNICAL HIGHLIGHTS

- makes SDR talk to commercial devices
- creates multiple radio interfaces on a single SDR for free
- enables infrastructure sharing
- makes real-time experimentation with SDR as easy as simulations
- offers flexible low-latency MAC-PHY architecture
- provides in-band full-duplex capable SDRs for high-throughput networking experimentation
- offers 5G mmWave system at 26 GHz with compact multi-beam antenna array
- offers hierarchical orchestration of end-to-end network slices through SDR-SDN integration

ORCA MAKES SDR TALK TO COMMERCIAL DEVICES



TAISC flexible MAC platform can talk to any IEEE 802.15.4 compliant commercial chips
With the native Linux driver framework, SDR behaves like a commercial Wi-Fi card

EASY CUSTOMIZATION ON TOP OF WELL-PROVEN WIRELESS STANDARDS

ORCA MAKES SDR TALK TO COMMERCIAL DEVICES

EASY CUSTOMIZATION ON TOP OF WELL-PROVEN WIRELESS STANDARDS

IEEE 802.15.4	CC2538 (commercial chip)	ORCA solution		
		Narrower BW	Standard	Wider BW
Data Rate (kbps)	250	31.25	250	2000
Bandwidth (MHz)	2	0.25	2	16
RTT (ms) [20 bytes in the air]	1.79	14.08	1.39	0.213
Sensitivity (dBm)	-97	-107	-98	-90
Range (m)	110	347	123	49

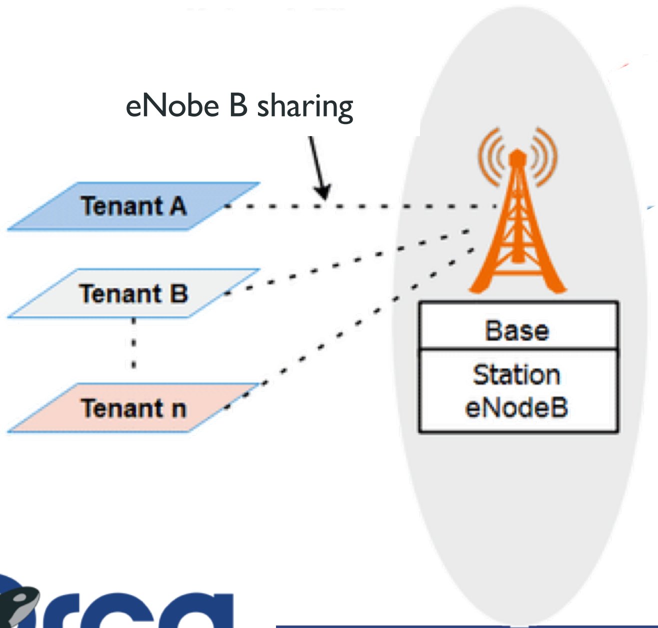
Low latency

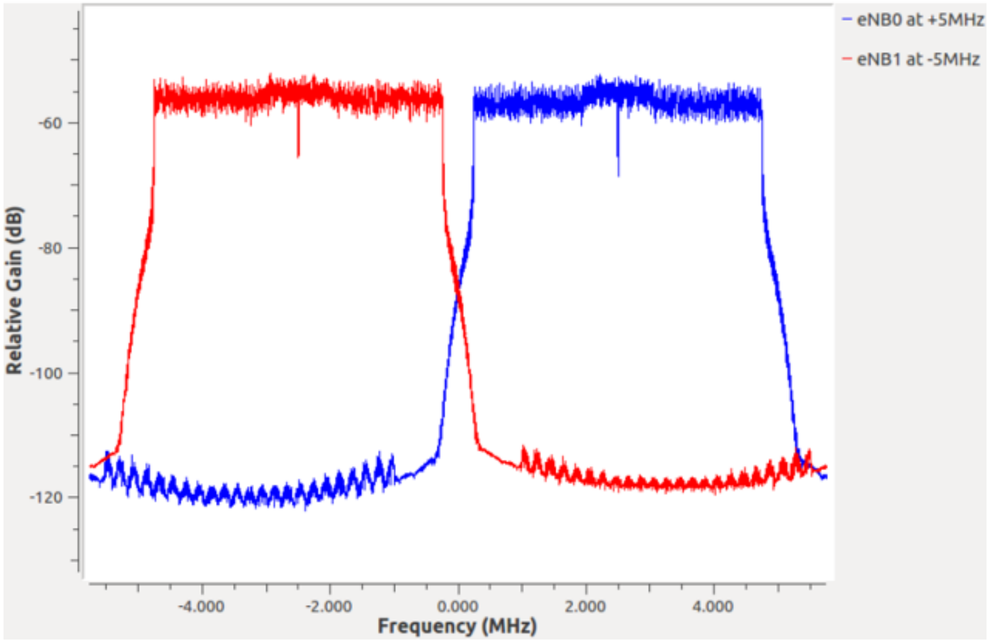
High reliability

ORCA ENABLES INFRASTRUCTURE SHARING

Virtualization: eNodeB infrastructure sharing

- Each operator uses its own spectrum
- Maximum 20MHz bandwidth achieved in total
- maximum 3 eNBs
  - 10+10MHz, 5+5+10MHz: 72Mbps
  - 5+5+5MHz: 54Mbps

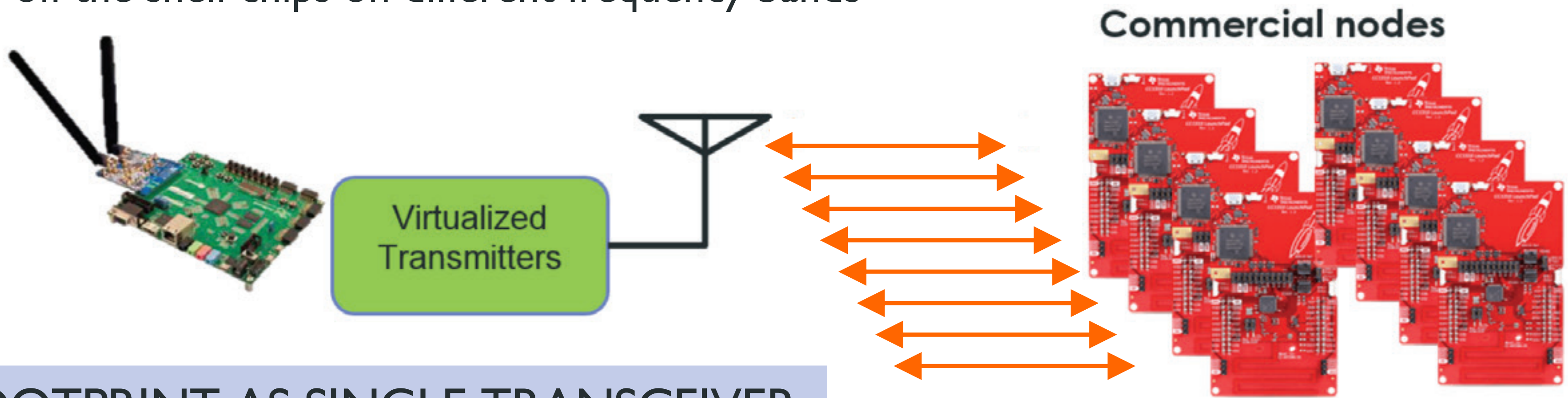




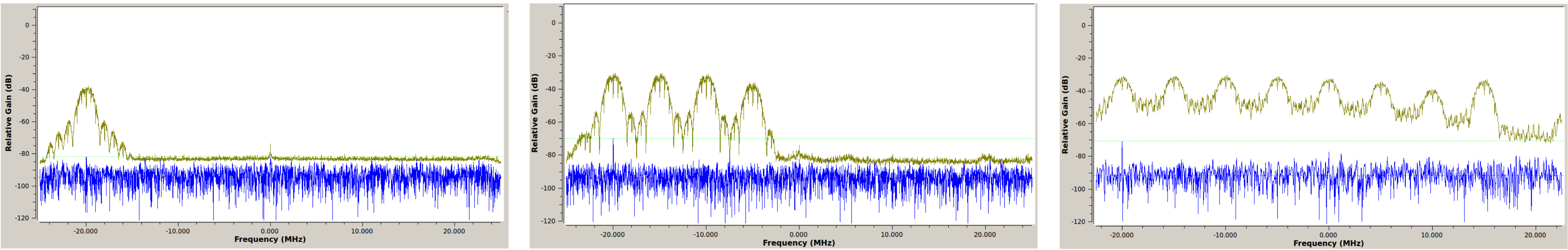
Runner up of best paper competition WiNTECH 2017

ORCA CREATES MULTIPLE RADIO INTERFACES ON A SINGLE SDR FOR FREE

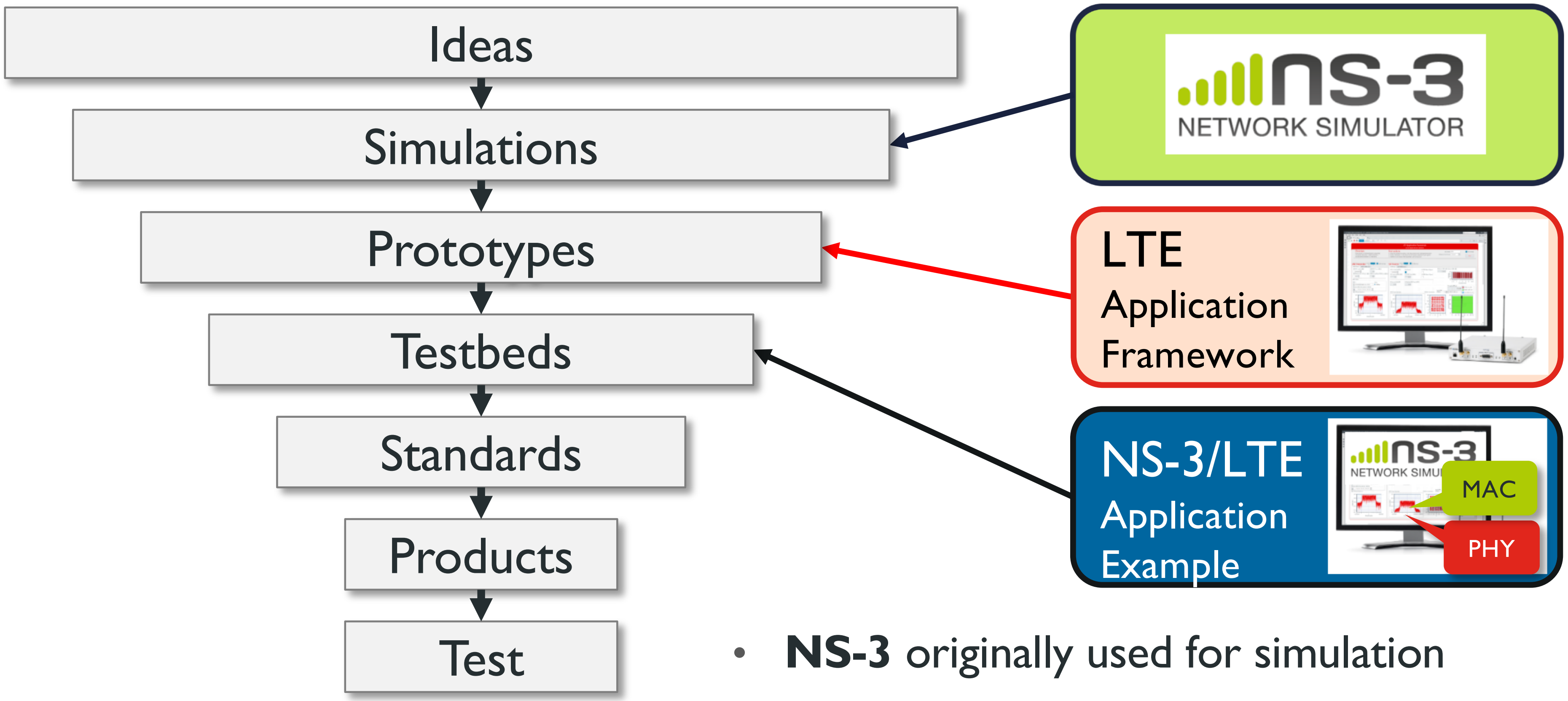
An SDR based hardware virtualized transmitter communicates concurrently with up to 8 commercial off the shelf chips on different frequency bands



SAME FOOTPRINT AS SINGLE TRANSCEIVER



REAL-TIME EXPERIMENTATION WITH SDR AS EASY AS SIMULATIONS

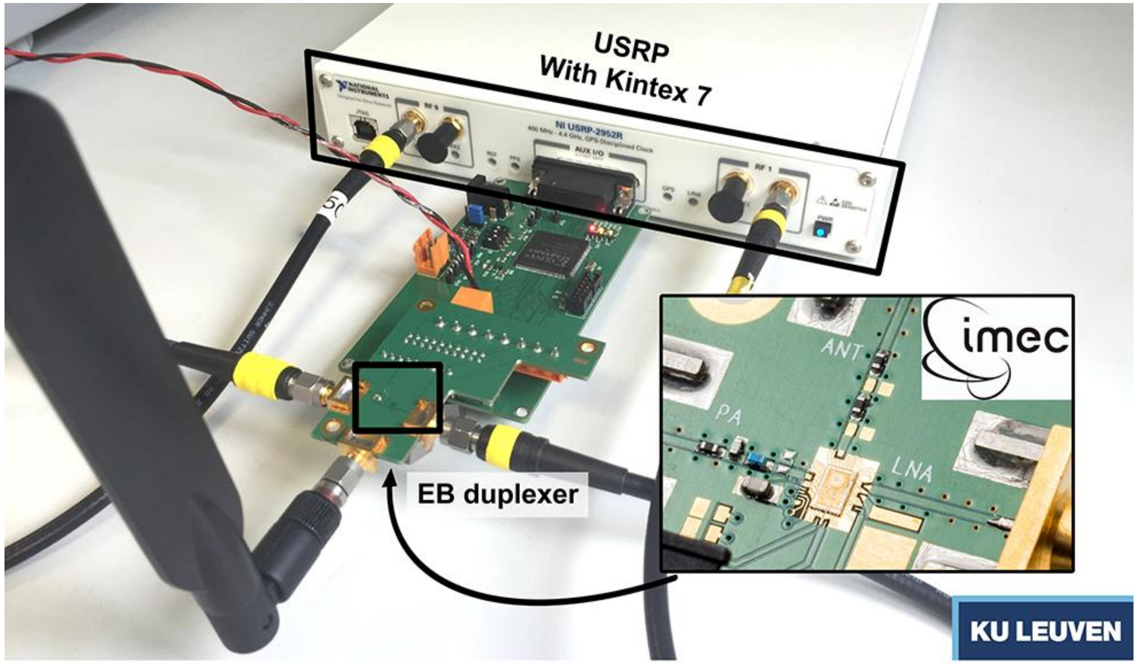


- **NS-3** originally used for simulation
- With **NI L1/L2 API**, experimentation in testbeds is as easy as simulation

ORCA OFFERS FLEXIBLE LOW-LATENCY MAC-PHY ARCHITECTURE

- Double layer MAC for low-latency performance
- Reconfigurable PHY and low-level MAC in hardware
- 1.3 ms round trip time, including PHY and MAC latency
- Run-time programmable high-level MAC

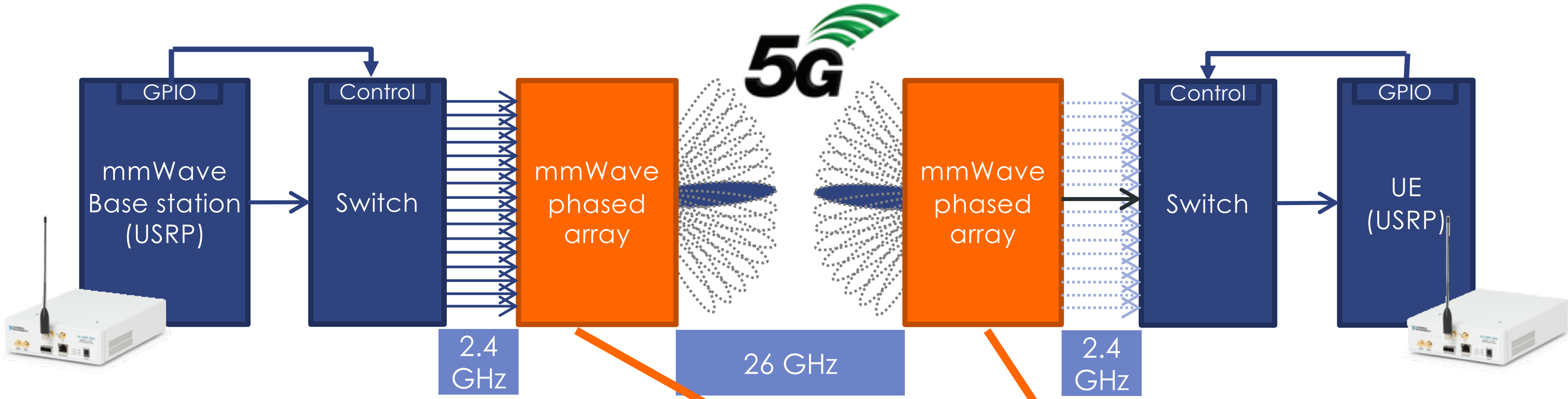
IN-BAND FULL-DUPLEX CAPABLE SDRs FOR HIGH-THROUGHPUT NETWORKING EXPERIMENTATION

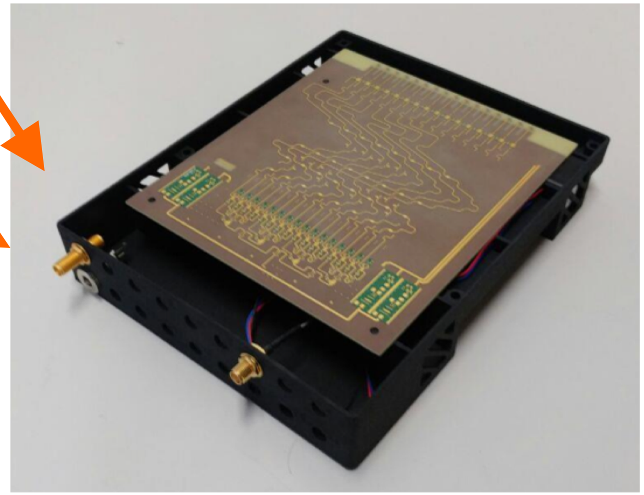


50 dB analog self-interference rejection

40 dB > digital Tx-Rx isolation

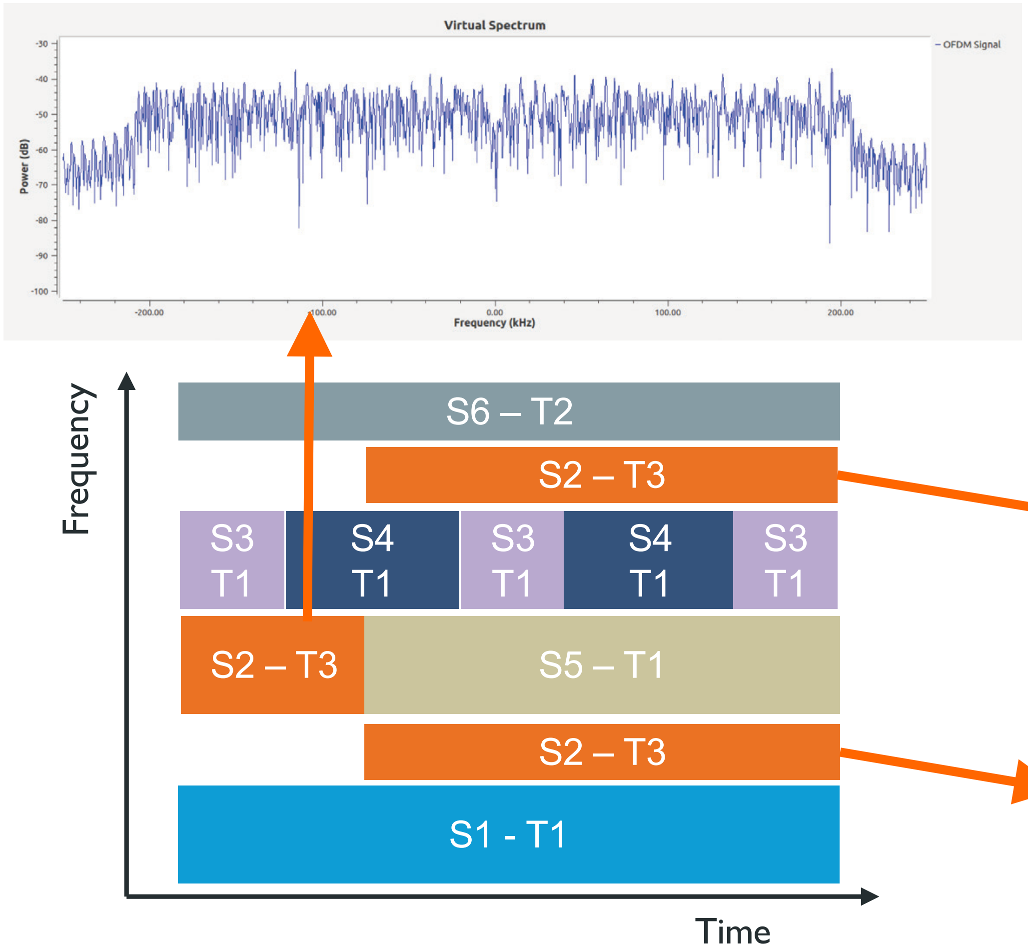
5G MMWAVE SYSTEM AT 26 GHZ WITH COMPACT MULTI-BEAM ANTENNA ARRAY



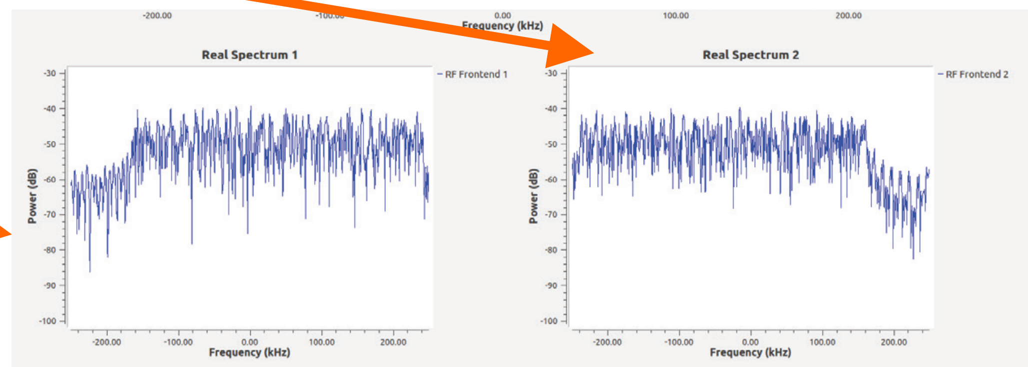


- GFDM PHY + up-conversion of USRP with an oscillator
- multi-beam antenna array with a 16x16 Butler matrix implemented with cost effective PCB technology

HIERARCHICAL ORCHESTRATION OF E2E NETWORK SLICES



- **SDR-SDN integration**
- Technology-neutral solution for the orchestration of resources across multiple wireless and wired network segments
- Dynamic radio slicing in time & frequency domain



ORCA FACILITY: ADVANCED SDR CAPABILITIES + TESTBEDS

- **Real-time, low latency** and high throughput operation
- **End-to-end** wireless experimentation (between end nodes, full stack)
- **Data plane** functionality
  - flexible design of PHY, MAC and higher networking layers
  - sub 6 GHz and mmWave technologies
- **Control plane** functionality
  - Runtime orchestration and parametric (re)configuration
  - SDR-SDN integration
- **Management plane** functionality: live HW and SW reprogramming
- Offered in advanced wireless **testbeds**

Orca = ACCELERATING INNOVATION

Experimentation with new radios BEFORE commercially available on the market

WIRELESS INNOVATION - HOW?

THEORETICAL ANALYSIS	SIMULATION	EXPERIMENTATION
☺ Link level models & analysis • PHY design • Channel models ☺ (Best case) system capacity models ☺ Static & deterministic systems ☹ Dynamic & non-deterministic systems ☹ Hard to model beyond PHY/link ☹ Hard to model realistic environments and wireless impairments: interference, multi-path, fading, shadowing… ☹ Hard to take into account hardware/implementation related constraints	☺ Network level analysis ☺ Easy implementation ☺ No need for hardware ☺ Controlled environment (e.g. topology) ☺ Scalability analysis ☹ Limited realism • oversimplified channel models • unrealistic scenarios • hard to simulate interference • hardware constraints not considered • synthetic data sets may not work • WRONG assumptions	☺ Realistic wireless environments (e.g. collision domain, coexistence, (self)interference, mobility…) ☺ Real hardware ☺ Real applications ☹ Limited by off-the-shelf hardware platforms and drivers ☹ More complex implementation • hardware dependent • often needs reverse engineering ☹ Small to medium scale experiments ☹ Reproducibility?

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EXPERIMENTATION

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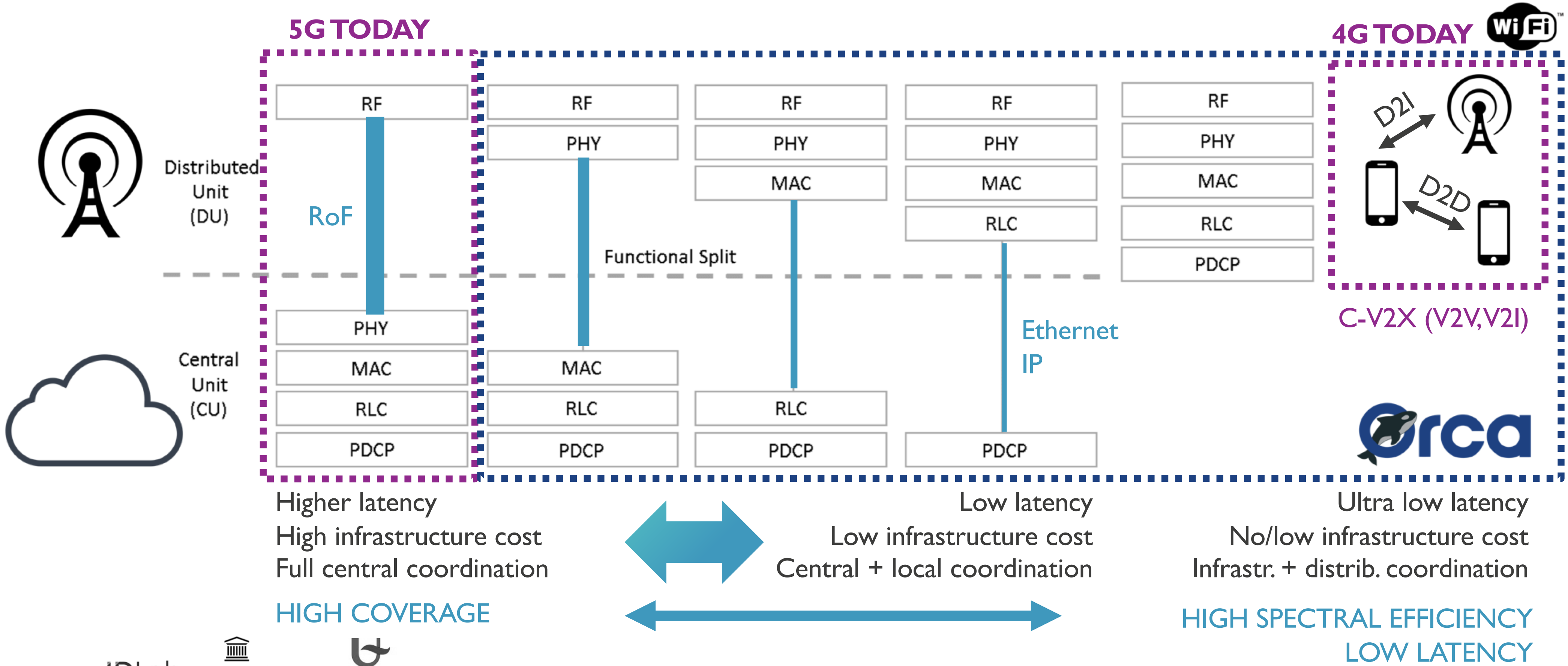
- ☹ Small to medium scale experiments

FUTURE VISION – 5G IS GREAT

DRIVERS FOR 5G - SOFTWARIZATION

- Using software rather than hardware to perform the processing of radio and network functions
- Great for non real-time (NRT) services, but RT services need hardware acceleration close to antenna

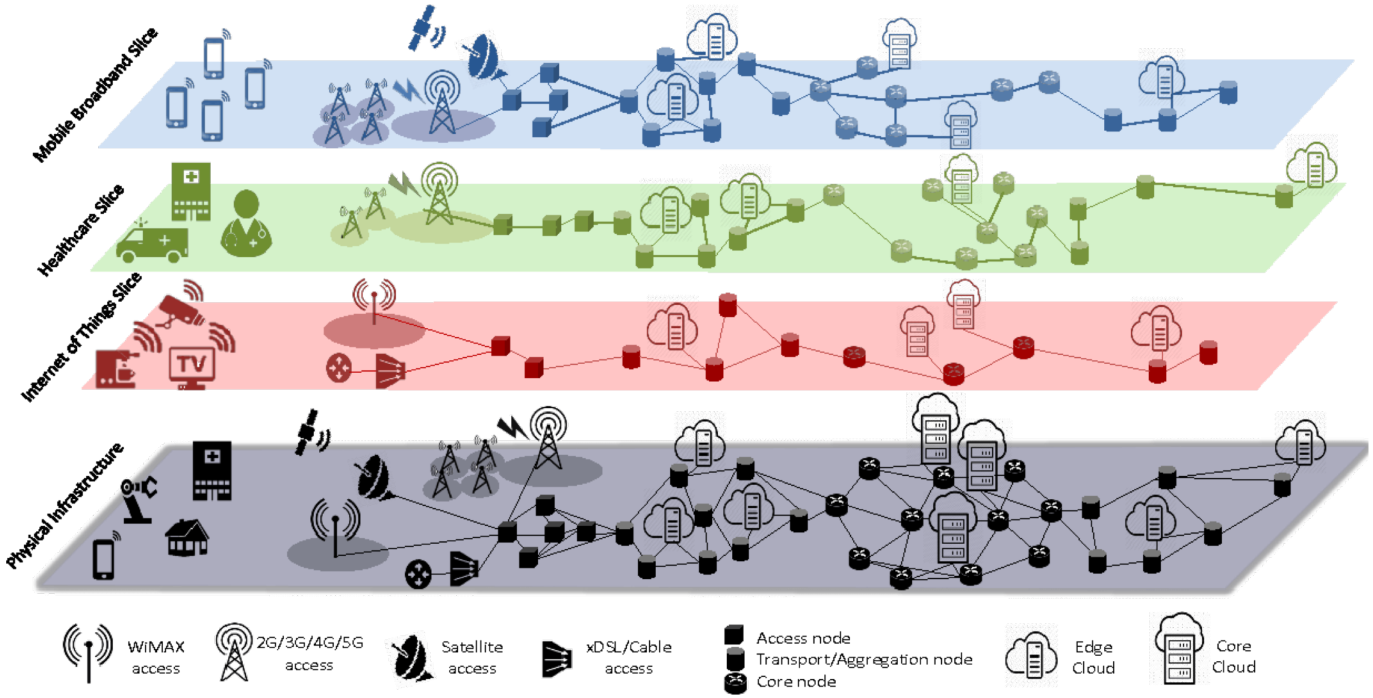


https://www-file.huawei.com/-/media/CORPORATE/PDF/mbb/cloud-ran-the-next-generation-mobile-network-architecture.pdf?la=en

DRIVERS FOR 5G - NETWORK VIRTUALIZATION

- Sharing of physical network resources by creation of isolated virtual networks (network slices)
- Each network slice can be individually configured to serve a particular purpose (vertical), guaranteeing a particular set of performance characteristics
- SDN centralized control of network slices

Orca offers radio virtualization and customization serving diverging needs within a single vertical



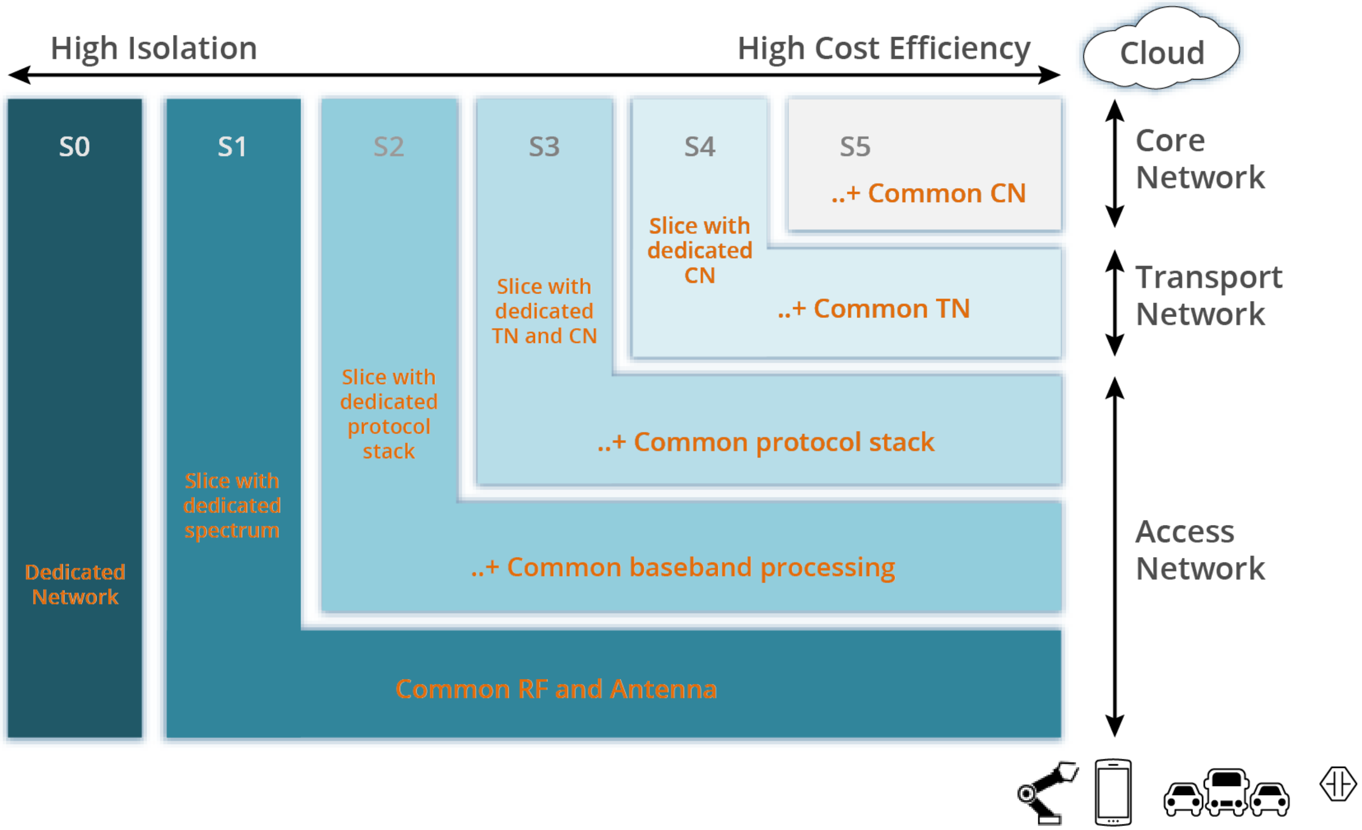
https://www.onug.net/blog/5g-network-slicing-and-enterprise-networking/

DRIVERS FOR 5G - NETWORK VIRTUALIZATION

- Isolation versus infrastructure sharing

Orca

- sharing of SDR infrastructure
- dynamic creation of isolated radio slices
- across heterogeneous technologies sharing the same spectrum
- SPECTRUM EFFICIENCY



https://www.huawei.com/minisite/5g/img/gsa-5g-network-slicing-for-vertical-industries.pdf

FUTURE VISION – 5G IS GREAT, BUT…

5G IS GREAT, BUT… SOME OBSERVATIONS

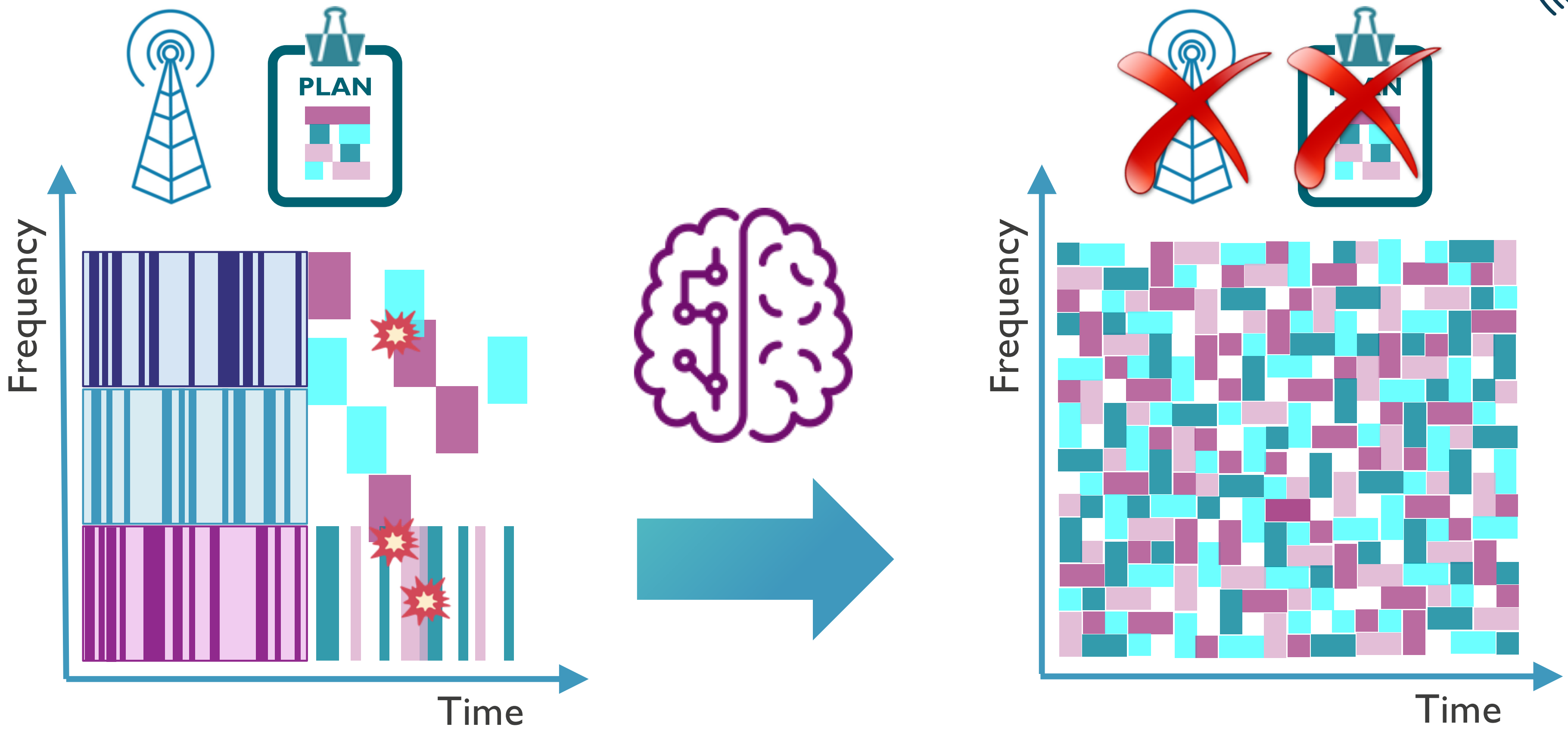
- **Trade-off between high coverage & spectrum efficiency**
  - new 5G spectrum allocation in sub 6 GHz band (in addition to 2G/3G/4G spectrum)
  - sub 6 GHz band is the most popular spectral band because of its favorable propagation properties
    - very attractive for low cost, low-power end devices
    - BUT spectrum in sub 6 GHz band is scarce and does not scale with increasing application needs
    - exclusive spectrum leads to waste (overprovisioning, as allocation is based on maximum load conditions)
  - MORE EFFICIENT SPECTRUM SHARING NEEDED RATHER THAN MORE EXCLUSIVE USE
- **Trade off between isolation and infrastructure sharing**
  - Network slicing access is led by NFV/SDN communities
  - Spectrum sharing and radio slicing requires fine-grained local control in wireless domain
  - ORCHESTRATION OF E2E SLICING WOULD BENEFIT FROM DOMAIN-SPECIFIC EXPERTISE

- **Holistic approach** with a "one system fits all" philosophy for supporting different verticals
  - complex and dynamic system with centralized control in the cloud
  - complex and time-consuming standardization process dominated by a few big mobile stakeholders
  - NEW AND SMALLER PLAYERS WOULD BRING INNOVATION

5G IS GREAT, BUT… SOME MORE OBSERVATIONS

- Softwarization is great, but low latency will require
  - less soft coding, more hard coding (hardware acceleration)
  - shift of functionality closer to antenna
  - more distributed control (D2D, V2V)
- Some smaller, local, indoor deployments, dynamic environments and niche markets may require local dedicated network solutions in full isolation
- Embedded hardware is also reprogrammable (soft code as well as hard code), cf. Orca
- 5G holistic approach can lead to vendor lock-in
- Do not ignore the role of service providers and local/private operators in future network development & deployment
- Do not ignore parallel evolutions, cf. DARPA spectrum collaboration challenge

DISTRIBUTED & COLLABORATIVE SPECTRUM SHARING



DISTRIBUTED INTELLIGENCE LEADS TO MORE EFFICIENT USE OF SPECTRUM!

DO NOT IGNORE INNOVATION IN END DEVICES

ORCA TEAM DOUBLE PRIZE WINNER OF DARPA SC2 COMPETITION

Dec. 2017

2 x
750 000 $

Dec. 2018

imec
RUTGERS
WINLAB | Wireless Information Network Laboratory

imec IDLab INTERNET & DATA LAB UNIVERSITEIT GENT Universiteit Antwerpen

FUTURE VISION – THERE IS MORE THAN 5G

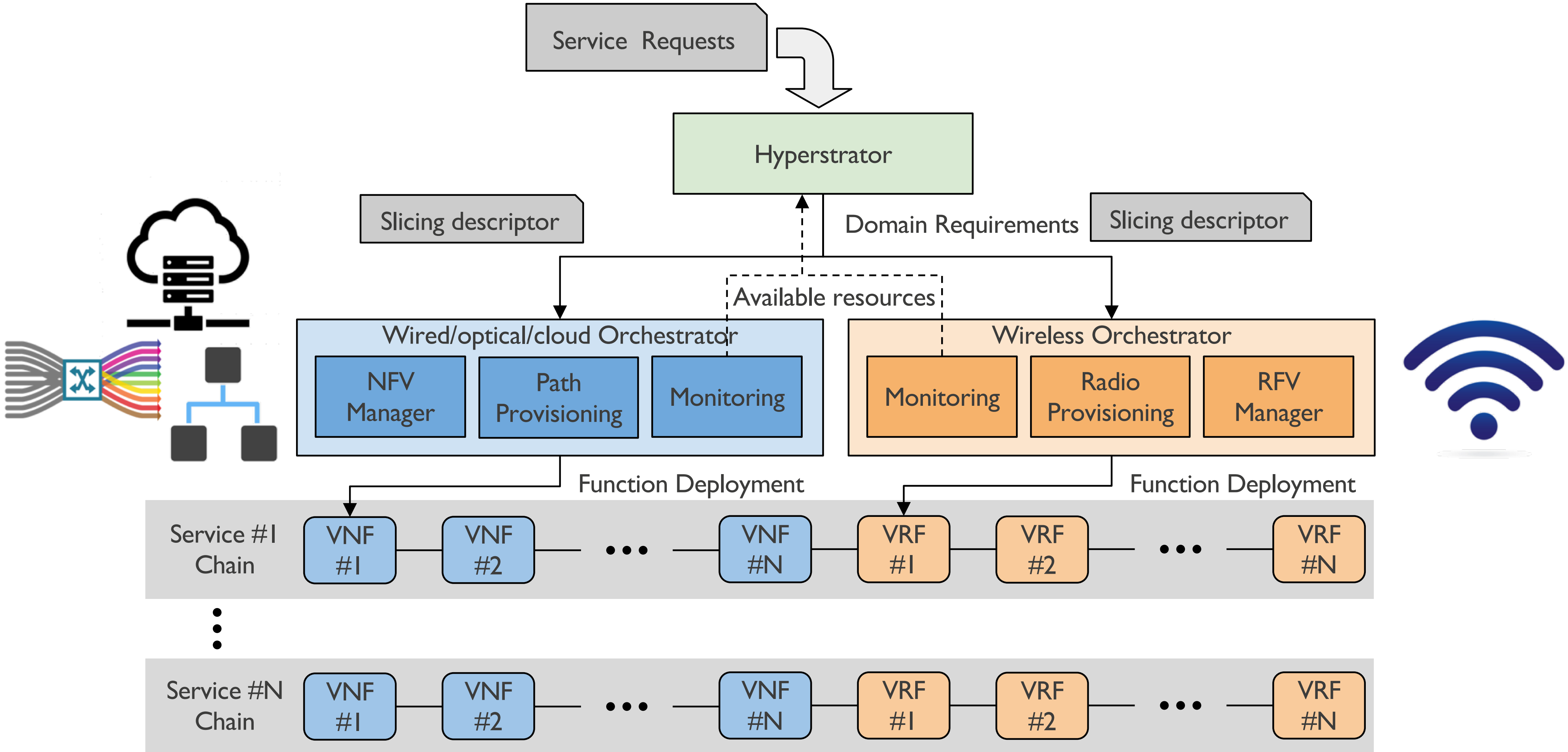
ORCA END-TO-END VISION

MOTIVATION

- DIFFERENT NETWORK SEGMENTS
  - built for different purposes
  - different media (optical fibre, copper cables, and wireless) with different technologies & protocols
  - HOW TO COMBINE INTO END-TO-END SLICE?
  - HOW TO GUARANTEE SUFFICIENT FINE-GRAINED RESOURCE CONTROL IN DIFFERENT SEGMENTS?

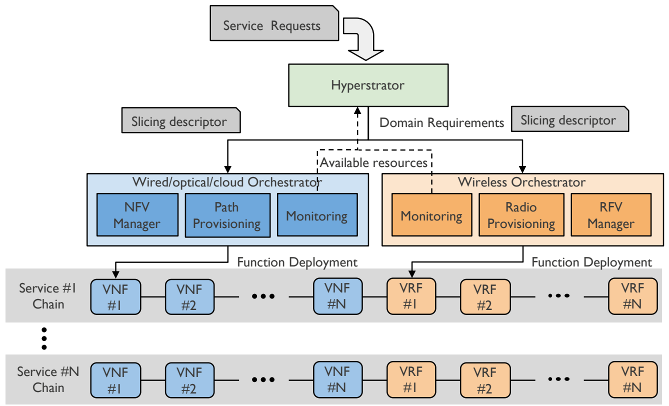
- WIRED VERSUS WIRELESS
  - wired: predictable and known capacity
  - wireless: variable capacity
    - due to the inherent stochastic nature of the wireless medium
    - due to interference (broadcast nature of wireless links)
    - due to mobility
  - DIFFERENT ABSTRACTIONS AND MODELS!

ORCA END-TO-END VISION: HIERARCHICAL ORCHESTRATION



ORCA END-TO-END VISION

HIERARCHICAL ORCHESTRATION



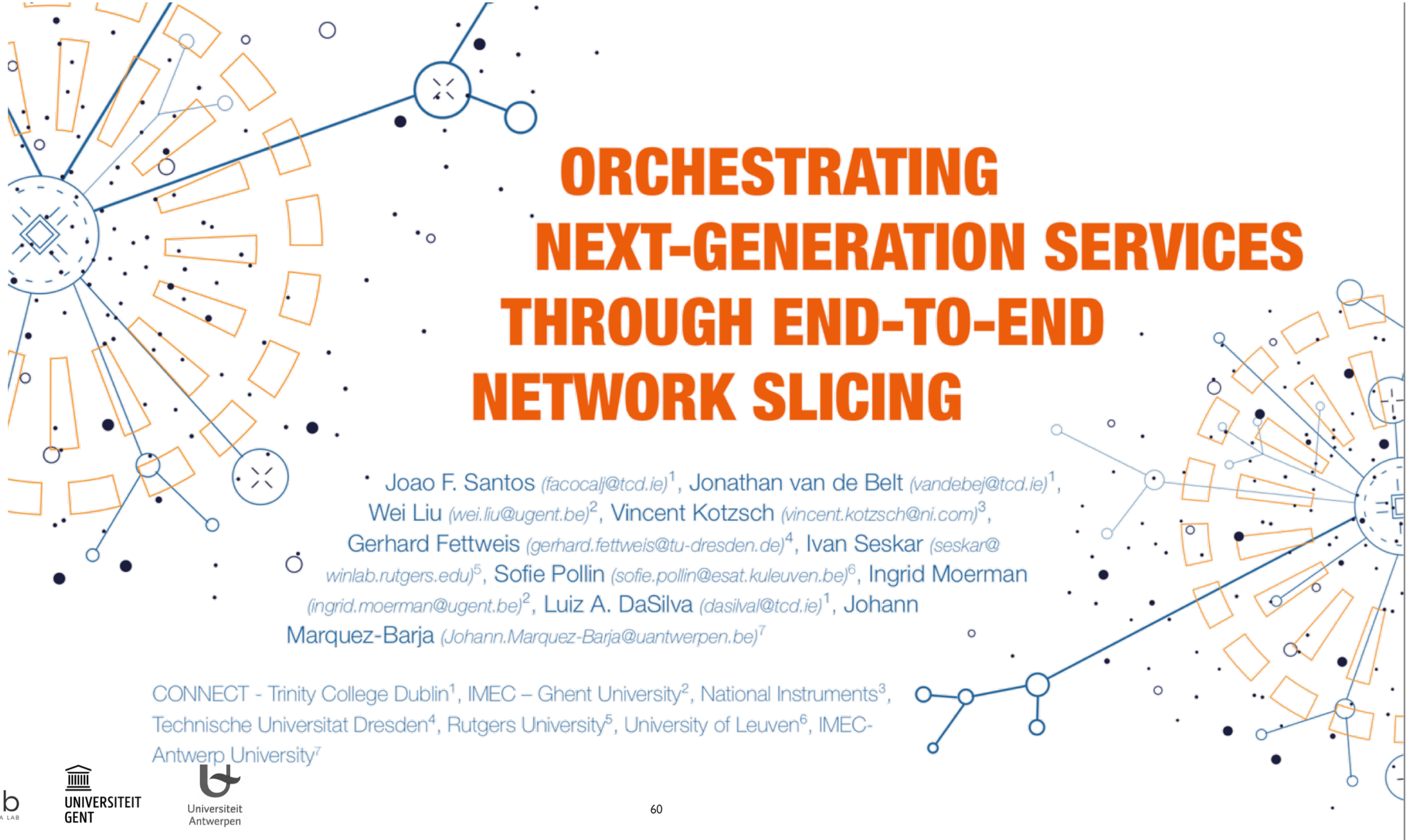
- HYPERSTRATOR
  - orchestrator of orchestrators
  - entity with a global view of the available resources and the capabilities of each orchestrator
  - coordination the interaction between the underlying virtualized infrastructure
  - aware of the ingress/ingress points between network segments
  - mapping high-level E2E network requirements into the requisites for the different networks segments
- Different types of ORCHESTRATORS for different types of segments
  - each orchestrator maps own requisites into a realization using the available virtualized resources
  - each orchestrator is responsible for its part of the service in the chain of virtual or physical network functions and radio functions

ORCA END-TO-END VISION: BENEFITS

- MODULAR: specialized segment orchestrator designed by domain experts
- ROBUST: less vulnerable to single point of failure
- UPGRADABLE: easy and independent changes or upgrades
- EXTENSIBLE: easy integration of orchestrators that manage additional/future types of network segments
- TECHNOLOGY NEUTRAL: not restricted to 5G technologies & specific spectral bands
- SIMPLIFIED STANDARDISATION
  - focus on open interfaces (1) expressing service requirements to hyperstrator and (2) expressing high-level functional description of slices between hyperstrator and underlying segments orchestrators
  - yields more freedom for solutions within segments
  - minimize risks of dependencies and lock in

ORCA WHITE PAPER

https://orca-project.eu/wp-content/uploads/sites/4/2018/10/orchestrating_e2e_network_slices_Final.pdf



ORCHESTRATING NEXT-GENERATION SERVICES THROUGH END-TO-END NETWORK SLICING

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INSPIRED BY…

Orca

Orchestration and Reconfiguration Control Architecture

THIRD OPEN CALL experiments

STAY TUNED

HERMES PARTNERSHIP

TEAM SCATTER

imec + Rutgers University

SPECTRUM COLLABORATION CHALLENGE